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MODERN DISPLAY TECHNOLOGIES FOR AIRBORNE APPLICATIONS
(U) ADVISORY GROUP FOR AEROSPACE RESEARCH AND
DEVELOPMENT NEUILLY-SUR-SEINE (FRANCE) G H HUNT ET AL.
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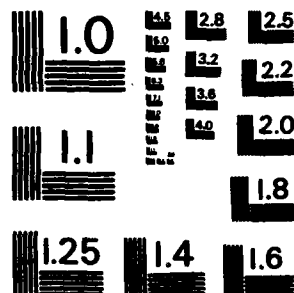
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1. Introduction
2. Background
3. Methodology

AGARD-LS-126

**NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT
(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)**

**AGARD Lecture Series No.126
MODERN DISPLAY TECHNOLOGIES
FOR AIRBORNE APPLICATIONS**

The material in this book has been assembled in support of a Lecture Series sponsored by the Avionics Panel, and organised by the Consultant and Exchange Programme of AGARD and presented in London, UK on 6-7 June 1983, in Rome, Italy on 9-10 June 1983, and in Fort Monmouth, New Jersey, USA on 16-17 June 1983

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- Improving the co-operation among member nations in aerospace research and development;
- Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;
- Providing assistance to member nations for the purpose of increasing their scientific and technical potential;
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PREFACE

→ This Lecture Series was recommended by the Avionics Panel of AGARD and is implemented under the Consultant and Exchange Programme. It has its origins in the AGARD Avionics Panel Working Group 11 on 'Modern Display Technologies and Applications' which was established in 1979 and reported in 1982, and is intended to promulgate the findings of the working group to a wider audience. The contributions to the Lecture Series have been made by authors from several nations, and represent their individual views and experience, although there has also been considerable interchange of views through the many meetings of the working group. to pg. v

The importance and timeliness of the topic of Electronic Displays for Airborne Application needs no justification; a cursory look at the instrument panels of recent military and civil aircraft shows the magnitude of the changes in technology that are now taking place. This change is a small subset of the changes in display technology and applications which are evident in many fields, and result from the increasing use of digital data processors and the need to efficiently interface them to human operators. Displays intended for airborne use have to satisfy a number of unusual requirements, which lead to design features specific to these applications. I hope that participants will find the presentations and discussions useful in providing an insight into this very interesting and rapidly changing branch of aerospace technology.

Geoffrey H. Hunt
Lecture Series Director



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CONTENTS

PREFACE
by G.H.Hunt

Page

iii

LIST OF SPEAKERS

iv

for
→ Contents includes:

Reference

→ INTRODUCTION AND OVERVIEW;
by G.H.Hunt

1

→ HUMAN FACTORS ASPECTS OF DISPLAYS;
by D.Bozman

2

→ COCKPIT ENVIRONMENT;
by W.M.Hollister

3

→ CATHODE RAY TUBES;
by J.P.Michel

4

→ IMAGE GENERATION ON MATRIX DISPLAYS;
by D.Bozman

5

→ LIGHT EMITTING DIODES;
by D.Price and K.Burnette*

6

→ LIQUID CRYSTAL DISPLAYS;
by A.J.Hughes

7

→ ELECTROLUMINESCENT DISPLAYS;
by B.Gurman

8

→ VACUUM-FLUORESCENT TUBES;
by J.P.Michel

9

→ LARGE AREA GAS DISCHARGE DISPLAYS OR PLASMA DISPLAYS;
by J.P.Michel

10

→ OTHER TYPES OF DISPLAY;
by A.J.Hughes

11

→ OPTICAL TECHNIQUES FOR AIRBORNE DISPLAYS; and
by G.H.Hunt

12

→ APPLICATIONS.
by W.M.Hollister

13

*These papers are given as supporting documents for the presentations made by Mr B.Gurman. Both these papers were printed in AGARD Advisory Report No.169.

INTRODUCTION AND OVERVIEW

by

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1 THE AIRCRAFT MAN-MACHINE INTERFACE

To fully understand the revolution that is currently taking place in aircraft displays, it is necessary to appreciate their function within the total aircraft system. In its most elementary role, a display provides an interface which allows information generated by the aircraft and its avionics equipment to be transmitted to, and absorbed by, one or more of the aircrew. The need for displays, and the principal factors in their design, are thus determined by this information flow and its characteristics.

In the early days of manned aircraft, and particularly prior to World War I, the avionics fit of aircraft generally comprised a number of individual items of equipment, each of which operated substantially independently of each other, and none of which had anything but the most rudimentary built-in intelligence. An example of the degree of intelligence might be the solution of a single differential equation in a lead-computing gunsight. Since that time the degree of intelligence contained within avionics systems has increased by many orders of magnitude, firstly by the use of analogue computation of various types, and more recently by digital processing. Individual sensors such as Forward Looking Infra Red equipments are also available which will generate data of high intrinsic intelligence. In addition it has become possible for individual avionics systems to communicate with each other at extremely high data rates, and thus operate in a highly integrated fashion.

At the same time, at the other side of the man-machine interface, there is the crew member whose individual intelligence is substantially unchanged, and the number of crew in each aircraft has been reduced to such an extent that many modern aircraft of high capability and sophistication are one-man operated.

The result of these changes is a situation comprising highly intelligent avionics systems, highly intelligent aircrew, and a very real problem in designing good communication interfacing between the two. It should be pointed out that these two types of intelligence are very different. Thus man talks to man with great ease, on-line by voice and by gesticulation, off-line principally by the written word and similarly digital processors talk to each other very easily using links and bus systems of enormous capacity. But inter-man communication and inter-processor communication are radically different, and no really 'natural' mechanism exists for communication between man and processor.

In designing a man-machine interface, there is considerable scope for changing the machine side and minimal scope for changing the man side. The man's existing sensors must be used, and the information must be presented to those sensors in a way which is as close as possible to the forms already familiar to him. This applies both in electronic displays, as will become apparent later, and also in the use of the sound channel.

Of the human sensors available for use in the interface, the eye has by far the greatest capacity as a receptor of information flow from machine to man. The other sensors (eg ear, fingers) have maximum rates of information flow which are orders of magnitude lower than those of the eye, but nevertheless are useful for particular types of signal. But the effect of the explosion in information capability within avionics systems has very largely fallen upon the display interface, and has resulted in the revolution in electronic displays which is now occurring.

The aircraft is not, of course, the only scenario for this interface between man and intelligent processors, indeed much of the preceding discussion could equally well have been said of a range of applications. Thus the drive towards new and more usable electronic displays has come from a much bigger market-place than the aircraft industry alone, and the development of new display types has been correspondingly rapid. The designers and manufacturers of new aircraft are thus able to exploit these new developments as they become available, adapting them as necessary to the particular problems of the airborne environment.

2 HISTORY OF AIRBORNE ELECTRONIC DISPLAY

The necessity for information to be available to the aircrew of piloted aircraft was realised from the beginnings of manned flight, and although in the early days considerable reliance was placed upon direct view of the outside world for both aircraft control and navigation, on-board instrumentation was also used. This instrumentation was installed primarily for measuring various parameters concerned with the condition of the aircraft, eg temperatures or fuel state, and with generating data on the aircraft's situation relative to the outside world, such as aircraft attitude, speed or position.

The instruments which measured these parameters were frequently sited in the cockpit and incorporated a form of read-out, such as a pointer on a dial, so that they could be directly observed by the pilot. It subsequently became desirable in some cases to position the instruments or sensors remotely from the cockpit and provide the indication within the cockpit by means of an analogue electrical data link. This evolution which has been described in depth by Chorley¹, continued into the post-World War II period. But already during World War II a start had been made towards using electronic indicators in the airborne field.

The earliest airborne electronic displays appear to have been cathode ray tubes which were used experimentally in the late 1930s, both in the UK and in Germany, in trials of airborne radar and airborne radio navigation equipment². In these cases the information being displayed was a raw, transient, analogue electrical signal which could represent, for example, the return radar pulse from some target aircraft, and for which any form of electro-mechanical display was clearly inappropriate. In a sense the CRT itself was a part of the radar, in the same way that the dial-and-pointer was a part of an early airspeed indicator. In spite of the many deficiencies of this type of display, they were used in several World War II applications as shown in Fig 1. Modern analogues of such displays exist in current military aircraft, in which the aircrew is still required to interpret relatively raw sensor data, for example in anti-submarine equipment.

The next major usage of electronic displays was also in military aircraft, and again the CRT was chosen. The need was recognised during the 1950s to feed information to a combat aircraft pilot while at the same time he was looking at real-world targets through his canopy. Already electro-mechanical gunsights had been developed, but by use of a CRT and suitable optics it became possible to provide both target information and other useful parameters such as airspeed and attitude. Thus was developed the head-up display which became standard equipment on most combat aircraft from the 1960s onward and which evolved into a truly multi-function display as more modes of operation were incorporated into the waveform generators and weapon system computers coupled to it. A typical head-up display of the 1960s period is shown in Fig 2.

From the late 1960s onwards, the usage of electronic displays has gathered pace in many applications outside the aerospace field, so that it was almost inevitable that many appropriate airborne applications would be found beyond the rather special cases described above. The whole spectrum of information requirements, as described in section 3 below, is now satisfied as well by electronic as by electro-mechanical display. Of particular interest is the realisation that primary flight instruments could be reproduced on CRTs, leading to the use of colour CRTs for this purpose on the most recent civil transport aircraft both in Europe and the USA. CRT displays used in this way had the important advantage, to be described later, that they could then be used for other purposes, which allowed different information to be presented at different phases in the flight, as well as when equipment failures of varying types occurred. At the other end of the scale of complexity, simple alphanumeric displays, using such techniques as liquid crystals and light-emitting diodes, are rapidly replacing electro-magnetic counters where dedicated displays of quantitative information are appropriate. The consequence of these developments is that for a wide range of both civil and military aircraft an increasing proportion of the information displayed to the aircrew is via electronic displays, as shown for example in Fig 3.

3 INFORMATION NEEDS

The information which has to be presented to aircrew by visual displays can be broadly categorised into three types:

- (a) information concerning the functioning of the aircraft as a vehicle, including particularly the status and condition of aircraft and engine systems;
- (b) information related to the guidance, control and navigation of the aircraft vehicle, including position, velocity and attitude relative to earth axes, and communication with ground stations;
- (c) information concerned with the operation of payload systems. For a military aircraft these will be principally the weapons and electronic warfare systems.

As avionics systems become more reliable and have greater computational and analytical capability, much of the information previously required by aircrew in categories (a) and (b) above becomes unnecessary except in system failure conditions. The aircrew's information needs therefore shift towards (c), and at the same time aircrew numbers may be reduced. This shift is illustrated by Fig 4, in which a number of typical tasks is listed and the degree of automation which may be achieved with each is shown, automation generally pushing the boundary line to the right.

For display designers, information requirements may be differently categorised according to the complexity (or information density) of the displayed information. In ascending order of complexity the following categories could be listed:

- (i) simple numerals and letters;
- (ii) simple fixed lines and areas;
- (iii) rotating and translating lines and symbols;
- (iv) any random arrangement of patterns and symbols;
- (v) as for (iv) with shading and colour.

There is an approximate correlation between this ascending order of complexity and the previous ordering of the categories (a), (b) and (c), which is particularly valid in the case of military aircraft where the representation of the battlefield scenario and of real-world images in a hostile environment requires a much higher order of information content than is needed for the stereotyped representation characteristic of the friendly civil scene. Thus in modern military aircraft there is strong emphasis on pictorial display in addition to the purely symbolic.

The design of displays has to take account of the type of information, but additionally must ensure that when presented on the display the information can be readily assimilated. There are obvious and well understood requirements in terms of information density, which is related to the resolution of the eye and of the display, and the dynamic effects associated with changing displays. Much more difficult are the human factors associated with perception, and the design of display formats to minimise error and workload tends to be rather an empirical process, heavily based on experience. The altimeter provides a clear example of this problem; the conventional electromagnetic instrument which was evolved after many years of work is shown in Fig 5, alongside an electronic display, a portion of which also shows altitude. Note how, even with the considerably greater freedom of design now obtainable with electronic displays, the resultant format corresponds very closely to the older design which was very constrained by mechanical design limitations. This is an indication of how the human factors dominates the design of a format much more than the physical constraints imposed by the display device itself.

4 PHYSICAL AND ENVIRONMENTAL CONSTRAINTS

Although electronic displays are now being adopted for many applications, it is generally not possible to take a display developed for some industrial or domestic application and use it in an aircraft cockpit. This is because of the very difficult physical and environmental constraints imposed by the aircraft application. The first of these constraints is imposed by the geometry of the cockpit. In most combat aircraft the displays are generally mounted on instrument panels which also carry switches and controls and have therefore to be beyond the ejection seat envelope but within the pilot's reach, thus the displays are usually 0.7 m to 1.0 m from the pilot's eye. To match display resolution to that of the eye then requires a line or element spacing of about three per millimetre. On the restricted instrument panel of a military aircraft the overall display size cannot be more than about 15 cm square, so that a matrix display of some 500 elements square is appropriate. These considerations are in fact very similar to those for displays used in office equipment.

The ambient lighting conditions in an aircraft are however very different. The wash-out of emitting displays caused by the sun shining through a canopy directly onto the display has required development of displays of much higher luminance than are used in most other applications. It has also led to the development of optical systems which prevent bright ambient light from being scattered back from the display surface. At the other end of the brightness scale is the need to operate at night with minimum emission from the cockpit and with minimum loss of aircrew dark adaptation.

Mention should also be made of the vibration levels; these can be very high in a military aircraft cockpit and demand a ruggedness of display construction which is much greater than for many applications. This has had a significant effect upon the development of airborne colour cathode-ray tubes.

5 ADVANTAGES AND DISADVANTAGES OF ELECTRONIC DISPLAYS

Electronic displays can be of such a wide variety that it is not possible to list the advantages common to all of them. In this context it is sensible to think in terms of two distinctly different types of display. The first, which is generally the simplest in physical construction, is relatively inflexible and can only display a limited range of symbols in fixed positions; an example of this is a row of alphanumeric characters. The second type has a high degree of flexibility, and in the limit can be thought of as the equivalent of a clean sheet of paper on which any message or picture can be drawn.

For this second class, the overwhelming advantage is the flexibility. This can provide either for a range of displays of generally similar type, eg alternate symbology displays, or at different phases of flight different types of display can be shown, eg TV-type pictorial displays for target acquisition during one part of the flight and symbolic displays for route planning during another. It is apparent that this characteristic of CRTs and high-density matrix displays can be of considerable benefit in the design of modern military aircraft cockpits. The additional flexibility provided by a multi-colour display such as a colour CRT is a further advantage which can have benefits in reducing the apparent clutter of some display formats and thereby easing the aircrew task.

The other principal advantages of electronic displays, which are common to the two classifications described above, are more concerned with their electrical and mechanical characteristics. Of particular importance is the fact that modern avionics systems are almost wholly based upon the computation and transmission of quantitative parameters by means of low-voltage digital signals. Displays which themselves are based on digitally-addressed arrays using similar voltages are therefore ideally suited for the display of these parameters, hence liquid crystal, light-emitting diode and other new types of solid-state display have a natural advantage. Cathode-ray displays are of course high-voltage and analogue and hence cannot claim this advantage.

Reliability and integrity advantages can also be claimed for electronic displays. Certainly their flexibility and the consequent possibility of designed-in redundancy give the cockpit/systems designers the possibility of improving the integrity of displayed information, provided the basic reliability of the display devices is sufficiently high. Although reliability of many of the newer technologies has yet to be fully established in service, there seems little doubt that as these technologies mature their inherent reliability will prove to be considerably greater than the electro-mechanical instruments which they have replaced. However, it should be noted that some of the earliest CRT displays, many of which are still in service, achieved an unenviable reputation of unreliability, principally due to the large number of discrete electronic devices which were of necessity incorporated in them; these problems have been completely overcome in the more modern displays.

Finally, mention should also be made of cost. There is no doubt that for small displays of numeric information, simple electronic displays are much cheaper in first cost than electro-mechanical counters. Cost comparisons between more complex electronic displays and their electro-mechanical equivalents are much more difficult, and really have to be made on the basis of total system costs, but with modern data processing it appears that the advantage in the future will lie with electronic displays.

The major disadvantages associated with electronic displays have always been the difficulty of overcoming the environmental problems described in section 4 above. With these problems now being steadily surmounted it is reasonable to assume that the overall balance of advantage will lie firmly in their favour.

6 INTRODUCTION TO THE LECTURE SERIES

AGARD Lecture Series 126 had as its origins the AGARD Avionics Panel Working Group 11, which was established in 1979 to study and report on the subject of 'Modern Display Technologies and Applications'. The main task of this working group was to review all the new technologies for electronic display in the context of the particular requirements and constraints imposed by airborne use. Thus it had to take note of the environment, the human factors aspects and the information presentation needs as well as the display technologies themselves. The working group reported its findings in 1982³. It may be noted that although the working group's report contains detailed information on all the technologies considered, and was able to suggest those technologies which were likely to be most suitable for certain classes of application, it was unable to predict with any degree of certainty that any one type of display would dominate in the future to the exclusion of others, simply because so many display techniques still had considerable potential for further development.

In 1982 it was agreed that the findings of the working group should be promulgated to a wider audience by the creation of Lecture Series 126. The subject matter is, therefore, closely similar in the two cases, as is the membership of the two. But in the Lecture Series there has been some opportunity to update in detail the contents of the working group report, and in addition a short lecture on optical techniques appropriate to airborne display has been added. In general, however, the working group report and the lecture series notes contain much common material. Although the state-of-the-art in display technology is advancing very rapidly, it is intended that most of the material published will have long-term usefulness in describing the fundamentals in display design and application, as well as providing information on current state-of-the-art.

The structure of the Lecture Series is as follows. Lectures 2 and 3 set the scene by describing the cockpit environment and the human factors aspects of displays considered as a man-machine interface. Lectures 4 to 11 cover the whole range of technologies, mostly describing individual types of electro-optic display devices except for Lecture 5 which discusses the common problems of addressing matrix displays, and Lecture 11 which covers optical techniques. Finally Lecture 12 takes all these technologies and considers how they are applied in the modern aircraft.

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3. AGARD, Advisory Report 169 of Avionics Panel Working Group 11 on "Modern display technologies and applications", 1982

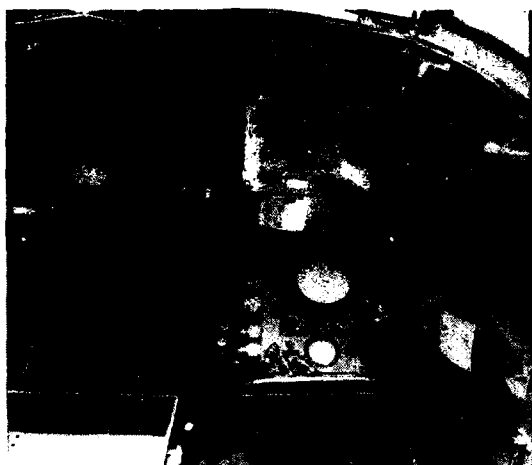


Fig 1 World-War II airborne electronic display (H₂S in Mosquito aircraft)

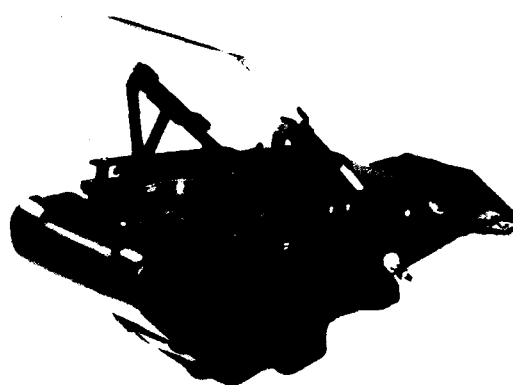


Fig 2 Typical 1960s head-up display

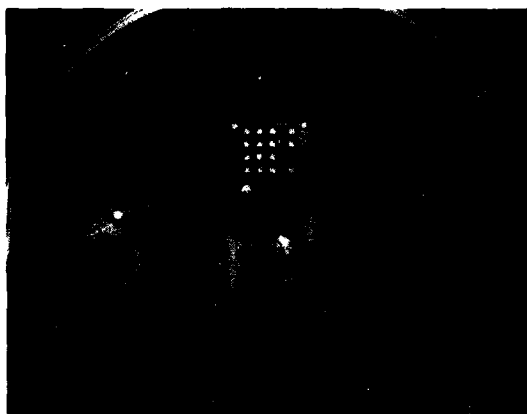


Fig 3 Typical modern military aircraft instrument panel

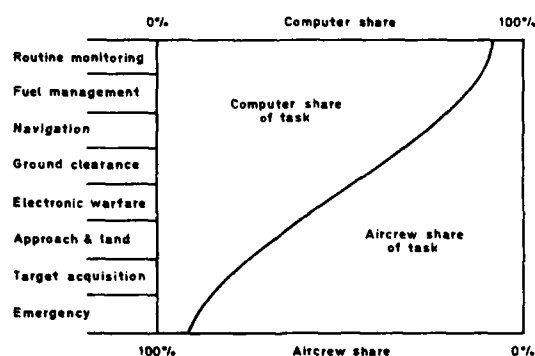


Fig 4 Sharing of tasks between aircrew and computer system

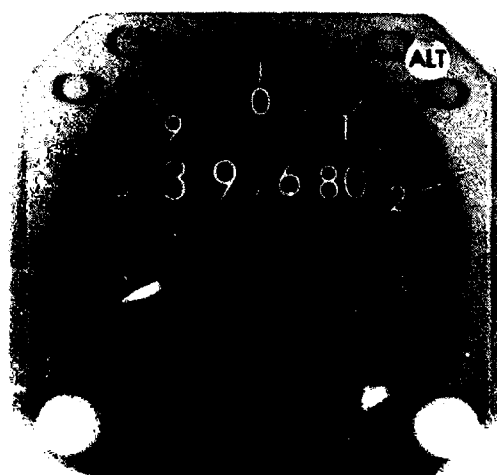
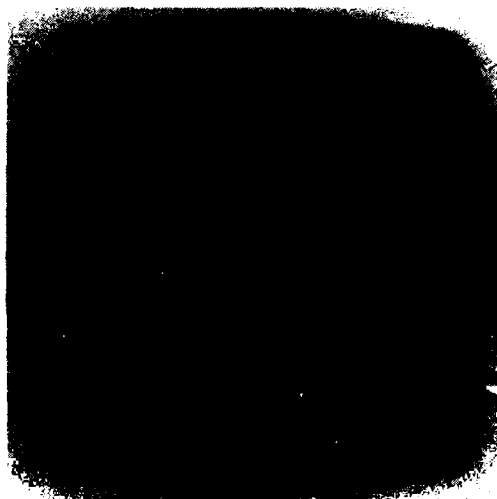


Fig 5 Altimeter presentations - electronic and electro-mechanical

HUMAN FACTORS ASPECTS OF DISPLAYS

by

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LECTURE 2

HUMAN FACTORS ASPECTS OF DISPLAYS

A total display system is a window, permitting the operator (pilot) to perceive the state and the dynamics of all the parameters which are relevant to his task.

The performance of the visual interface between machine and brain is determined by technical and ergonomic factors. Many of these are described in this chapter, in order to provide a basis for better interpretation of such data in assessing display performance specifications.

The main technical factors are:

- optical, including luminance contrast and color contrast of the display in its environment, the sharpness and steadiness of its image, and other technical qualities such as absence of distortions, spatial homogeneity of addressed and background areas/segments, independence of contrast of viewing angle, etc.
- image generation, from addressing techniques to quantization effects (Lecture 5).

The main ergonomic factors are for the purpose of this report grouped into the following categories:

- viewing characteristics as a function of environment/surround conditions, including luminous efficiency and temporal response of the eye, visual acuity, contrast thresholds as a function of the eye's adaptation state, visual search data, sensitivity to flicker.
- legibility of displayed symbols.
- factors associated with the use of color. Although colorimetric data pertain to the domain of physics, the perception of color as used in e.g. a display is a human factor.

2.1 THE TECHNICAL FACTORS AFFECTING THE PERCEPTION OF DISPLAYED DATA

2.1.1 OPTICAL FACTORS

First, some definitions of the field of optics will be recalled.

The radiant energy Q_r of a light emitting display is only partly emitted in the form of luminous energy Q_v ; a major fraction is spectrally located in the near and far infra-red regions, causing heat which must be dissipated along well defined and controlled channels. The associated IR emission can be troublesome; interference can occur with night vision systems on the aircraft and IR radiated from the cockpit adds to its detectability.

The radiant flux, or power P_r , is equal to the rate of flow of radiant energy. The distribution $P_r(\lambda)$ of power over the contributing components with wavelength λ is the power spectral distribution of P_r . In Fig. 2.1 the normalized spectral distributions for a 2000 K radiating black body, a green and a red light emitting diode (LED), and a P43 phosphor are depicted. The larger the area under the curve, the more overall energy is radiated.

If a photo-sensitive sensor is stimulated by P_r , its sensitivity being also dependent on the wavelength λ , its output will be the weighted sum of radiated power and sensitivity:

$$\int S(\lambda) \cdot P_r(\lambda) \cdot d\lambda \quad (2.1)$$

In the case of the eye/display system, and assuming that the non-luminous fraction emitted and/or reflected by the display is neither hazardous nor irritating, one is only concerned with the radiant power which stimulates the sensors in the human eye. The luminous flux F is equal to the experience of visual stimulation brought about by P_r .

The luminous efficacy function $K_m V(\lambda)$ of the human eye varies with the wavelength λ and with the intensity of stimulation, see Fig. 2.7. The sensation of light thus is weighted by $K_m V(\lambda)$:

$$F = \int F(\lambda) d\lambda \text{ or } F = K_m \int_{400}^{750} V(\lambda) \cdot P_r(\lambda) d\lambda. \quad (2.2)$$

The integration interval is in practice determined by the luminosity interval outside which $V(\lambda)$ is almost zero. The unit of luminous flux is lumen, K_m is lumen per Watt. Under photopic conditions, K_m is 673 lm W^{-1} , under scotopic conditions 1725 lm W^{-1} (see section 2.2.1).

In light emitting displays the fraction Q_v/Q_r usually is very small. For reflective type displays, the energy of (desired) reflected light (both diffuse and specular) can be much higher. This does not automatically mean that they have superior viewing characteristics, since Weber's law states that contrast perception is constant if the just noticeable difference (JND) of luminance ΔL between two adjacent surfaces is proportional to the absolute luminance of the duller surface.

To relate luminance, illumination and brightness to luminous flux the following is appropriate (2.1), (2.2).

- for a point source, the luminous intensity I (candle-power) is the luminous flux per unit solid angle $\frac{dF}{d\omega}$ (see Fig. 2.2.a) in lumen per steradian (lm sr^{-1}) or candela (cd);
- the illuminance E is equal to the luminous flux per unit area $\frac{dF}{dA}$ (incidence normal to the surface), expressed in lux (lx).

Illuminance is a measure of the flux received by a given area;

- An illuminated, non-black surface will reflect some of the light incident upon it, partly specular, partly in a wide range of directions (diffuse). The surface thus resembles a self-luminous surface. The emitted luminous intensity per unit projected area is the luminance $L = \frac{dI}{dA \cos \phi}$ (see Fig. 2.2.b), its unit being cd m^{-2} (nit). Luminance measures the flux emitted in a given direction. A much used practical definition is: a uniform diffuser which emits a total flux of 1 lm cm^{-2} is said to have a luminance of 1 lambert (L, not a SI unit):

$$1 \text{ L} = \frac{1}{\pi} \cdot 10^4 \text{ candela m}^{-2}.$$

- The perceived luminance or brightness is determined by the retinal illumination. In Fig. 2.2.c the surface element dA_1 emits, in a direction with angle ϕ normal to its surface, a flux F with luminous intensity dI . The area A_2 of the pupil of the eye transmits the fraction dF of the flux F onto the retina, where the image dA_3 is formed of the emitting surface dA_1 .

Now:

$$dF = dI \frac{A_2}{r^2} = L dA_1 \cos \phi \cdot \frac{A_2}{r^2}$$

The area of the retinal image dA_3 is roughly equal to

$$dA_3 = dA_1 \cos \phi \cdot \frac{l^2}{r^2}.$$

wherein r : distance of the observed surface to some point in the eye lens and l : separation between the retina and some (other, but close) point in the lens. Consequently the retinal illumination is determined by:

$$E_v = \frac{dF}{dA_3} = T_v \frac{L \cdot A_2}{l^2} \quad (T_v: \text{transmission factor of the eye}) \quad (2.3)$$

and thus the brightness sensation is not dependent of the area A_1 of the surface observed, neither of the distance r , nor of the angle of inclination ϕ ; however, it is linearly dependent of its luminance L provided the pupil area A_2 remains constant. However, the above does not apply to point sources (element size near limit of visual resolution) such as Light Emitting Diodes (LED's). The unit of retinal illumination is the troland: $L.A_2$ (nits mm^2).

When diffusely emitting or reflecting surfaces are observed, the brightness often seems independent of the angle of inclination of the surface. This property is very useful in displays, as it affords a wide viewing angle. From the considerations about the retinal illumination it follows that the emitted luminous intensity per unit projected area, or luminance L , must remain constant, irrespective of the radiation directions. Since the definition of luminance is $L = \frac{dI}{dA \cos \phi}$, the luminous intensity I must follow a cosine law: Lambertian radiation (Fig. 2.2.b).

A luminous surface which exhibits this characteristic is called a uniformly diffusing surface.

There are many optical units in use, although the SI (Système International) units given here are preferred. In the British system:

- luminous flux is expressed in lumen,
- luminous intensity: candela,
- illuminance: 1 foot-candle (1 m ft^{-2}) = 10.76 lux,
- luminance: candela per square foot (cd ft^{-2}). A uniform diffuser which emits a total flux of 1 lumen per square foot has luminance of 1 foot-lambert:
(1 fL) = 3.43 cd m^{-2} .

To understand the conversion factor between the foot-lambert and cd m^{-2} , or between the lambert and the cd m^{-2} , one must realize that the uniform diffuser emits light in all directions, whereas the candela relates to only the solid angle of one steradian. It can be shown that the luminance L of a uniform diffuser which emits a flux of P lumen per square meter is: $L = \frac{P}{\pi}$. Thus the conversion factor between the foot-lambert and the candela per square meter is $(\frac{\text{m}}{\text{foot}})^2 \cdot \frac{1}{\pi} = 3.43$.

Practical numbers for the luminance of e.g. suitably mounted cathode ray tubes (CRT's) are:

- office use, computer terminals: $50\text{-}200 \text{ cd m}^{-2}$.
- aircraft, HUD: green display line 5.10^3 cd m^{-2} , provided that there is adequate color contrast against the background.
- aircraft, HDD: 3.10^4 cd m^{-2} .

2.1.2 CONTRAST DEFINITIONS

To achieve such high luminances is a difficult engineering problem, solved at the cost of high power dissipation. The high luminance is, however, only required to contrast against high background luminance. It has been shown that people do not require very high levels of luminance contrast on the display face, so that the average power dissipation can be markedly decreased by controlling the light output of the display to match the adaptation state of the eye caused by the mean retinal illumination in the broad field of view, in order to keep contrast within a small acceptable range.

Filters can be used to reduce the effect of illumination falling directly on the display.

As already stated, the concept of contrast is a controversial notion. There is luminance contrast (achromatic or irrespective of color), color contrast (at equal luminance) and a combination of both (2.3). These concepts can be defined exactly and reproduced under laboratory conditions. For instance, luminance contrast threshold is measured when a small (e.g. 10 mm) symbol such as a disc, a ring with a square gap or a numeral with a (foreground) luminance L_f is just noticeable against a large, wide angle of view, background with luminance L_b when L_f/L_b or L_b/L_f exceeds a threshold value.

One may define e.g. the luminance contrast and modulation depth:

$$C_r = L_f/L_b, C_v = |L_f - L_b| / L_b, MD = (L_f - L_b) / (L_f + L_b). \quad (2.4)$$

C_r (contrast ratio) is the simpler definition and is used much in engineering. Although C_r can be easily converted into C_v through $C_v = |C_r - 1|$, "visual" contrast C_v seems to be the logical choice when the eye is involved because the law of Weber-Fechner states that the perceived sensation is a logarithmic function of the stimulus (in other words, the just noticeable difference ΔL is proportional to L). If $C_v = \frac{\Delta L}{L}$ must remain constant irrespective of L , the display driving variable h_q (section 5.2) must cause a luminance $L(h)$ according to $L(h) = L_0 e^{\gamma h}$, in which γ is a contrast gain factor since now $\frac{\Delta L}{L} = \gamma \Delta h$. So, when Δh is the least significant bit (LSB) of the numerical image in the computer, the ratio $\frac{\Delta L}{L} = \gamma$ corresponding to $\Delta h = 1$ must equal the JND (just noticeable difference) of luminance in continuous grey level images ($JND = 0.03$ for large areas). In graphic displays $\frac{\Delta L}{L}$ is chosen in steps of $\sqrt{2}-1 = 0.42$. Fig. 2.3 shows this relationship for $L(h)$ and $MD(h)$, $\gamma = \ln 1.03$. The Modulation Depth (MD) is more appropriate to the practice of flying where the luminance distribution is more complicated than under said laboratory conditions. A display is composed of a number of symbols and lines: when looking at one symbol, all the other foreground luminances merge into the background and contribute to perceived contrast as modelled by the denominator of MD. Fig. 2.4.b gives the resulting MD calculated for overlapping smooth display spots (e.g. of a CRT), situated as shown in Fig. 2.4.a.

In psycho-physical measurements of contrast sensation MD is also used. The contrast sensitivity at threshold (50% detectability) equals its absolute reciprocal: $CS = |MD|_{th}^{-1}$. Since under laboratory circumstances L_f , L_b and their respective areas are well controlled, CS is good scientific measure (see Figs. 2.6, 2.13, 2.14).

Table 2.1 below shows that the relationships of MD and C_r are logarithmically symmetric in the region of interest $.1 < C_r < 10$, C_v follows C_r closely for light-on-dark symbols but tracks MD for dark-on-light symbols.

Table 2.1

C_r	C_v	MD	CS
0.1	0.9	- 0.818	1.22
0.2	0.8	- 0.666	1.50
0.5	0.5	- 0.333	3.0
1	0	0	∞
2	1	+ 0.333	3.0
5	4	+ 0.666	1.50
10	9	+ 0.818	1.22

The light and color adaptation state of the eye is further influenced by surround luminance L_s , which is emitted or reflected from surfaces in parafoveal view. Also, the eye may be conditioned to outside luminance (from peripheral angles) when looking at the display: veiling luminance L_v .

Of course, to complicate matters, the logarithmic law (Weber-Fechner) is valid over only part of the range of luminance encountered in flying. Further, L_b and L_s can be composed of display (emissive) luminance in combination with (display) reflective luminance due to environmental light falling on both the display and the instrumentation panel.

The reflections may also have a specular and a diffuse component, causing the distribution of MD over the display face to be non-uniform. The detrimental effect of reflections, in particular specular, can be decreased by the use of light absorbing (black) background materials in the display and of specially designed display face materials and front covers. Transparent covers for active displays may be neutral having

a low transmission factor (< 0.3); or color dependent, possessing a transmission factor which is very low throughout the spectral range except for display emission wavelengths. They enhance the contrast by decreasing the effect of environmental light on L_b because reflected external light which penetrates the cover travels twice through it and thus is attenuated twice, whereas pixels and display background emissions are attenuated only once, as depicted in Fig. 2.5. However, such covers do not materially help to reduce the dimming range, unless the transmission factor of the cover can be controlled as function of the background luminance level (photochromic, electrochromic materials). But at very low light levels, where the display surface hardly reflects any light, a low transmission factor of the cover reduces L_f without contrast enhancement. Since visual acuity (2.2.2) (or high frequency CS) deteriorates rapidly with low light level, wider lines and higher letters (zoom facility) seem to be the only real alternative to maintain legibility in the complete dark without (partially) blinding the pilot. In the cover with controlled transmission (2.23), the transmission factor should again become low at the high end of the L_b range to reduce the background luminance so as to enable the designer to cut the power requirement of the CRT (lower L_f) to advantage.

In some types of display the addressed pixels become visible through polarizers, or contrast enhancement is effected by a polarizing cover. The application of such displays must be carefully considered when the pilot or observer is likely to wear polarized glasses!

Because the viewing performance depends on contrast, and the contrast requirement depends on luminance level also resolution, it is recommended to control foreground luminance to keep MD within comfortable tolerance limits ($0.15 < MD < 0.8$). Simultaneously the L_b should be controlled to match surround luminance L_s , thereby attaining a uniformly distributed light level across the instrument panel so that adaptation delays are not incurred when switching attention. Also non-uniform brightness suggests to the observer that there are (intended) differences in attention value of displays: luminance and contrast of multiple displays must be approximately matched.

The question: what is the extend of the visual field which must be considered, has not been answered with any great precision. Blackwell (2.21), see section 2.2.4 and Fig. 2.13, has theoretically determined the contrast thresholds required to see a disc of variable size (area) under different background luminance conditions (adaptation state of the eye), but the applicability for edges other than contours around larger areas is questioned.

2.1.3 RESOLUTION

An optical system will cause decrease of sharpness (blurring). This is true for a lens (system), however well focussed, and for an electronically addressed display. Blurring is evidenced by the fact that an infinitely small point source in the original image plane is reproduced as a dot of finite size (circular for the cathode ray tube or CRT, with an intensity gradient at the edges). The function which describes the blurring is called the Point Spread Function (PSF). Because blurring occurs for every point in the original image, one may describe the image in the presentation plane as being the result of convolving the original image with the PSF. If the PSF is invariant, irrespective of location of the pointsource and of time, the process is linear, time invariant.

The resolution of an optical/imaging system is determined by the separability of two or more closely located points or lines, each smeared by the PSF as shown in Fig. 2.4.a and b. The resolving power depends on the luminance-contrast C_r (or MD) and on the signal to noise ratio SNR at the detector which, for a display, is the eye/brain system. C_r (MD) depends on the peak to peak luminance difference $L_f - L_b$ which generally decreases with decreasing distance (Fig. 2.4.a). If the stimulating image is a harmonic grating, the resolving power at the given spatial frequency is obtained when the contrast sensitivity at threshold equals the modulation depth remaining after convolution with the PSF (limiting resolution). It is possible that C_r/MD changes sign at very high spatial

frequencies: contrast inversion.

2.1.4 SPATIAL FREQUENCY RESPONSE OF OPTICAL SYSTEMS AND DISPLAYS

One may obtain another description of the imaging characteristics of an optical/imaging system by taking the Fourier transform of the PSF: the result is the Modulation Transfer Function (MTF). It describes how well the frequency components of a two-dimensional image are reproduced by the imaging system. The spatial frequency components of the image are defined as the number or cycles per mm or, at a given viewing distance, cycles per degree of visual angle. The modulation depth (MD) at each spatial frequency is the dependent variable, see Fig. 2.6.a, which depicts the MTF's associated with a soft and a hard PSF. In the case of the display it is assumed here that the reproduced image is continuous (not sampled either horizontally or vertically) and that a sufficient number of gray scales is available such that the MD may also be considered continuous. Grey scales are for continuous images defined as contrast ratio levels which differ by factors of 1.03 or less.

The MTF of an optical system can be determined by its supra-threshold MD response to sinusoidally modulated gratings or by measuring the PSF with a micro densitometer and taking its Fourier transform (2.4). In general, the larger the area under the MTF, especially at the high frequency end, the more details can be distinguished in the image. Thus, by increasing the contrast for high spatial frequencies (image processing), one may compensate for blur.

Above it was assumed that the PSF is invariant and, by implication, also the MTF is invariant. However, for the visual system (Fig. 2.6.b) they depend on the adaptation state of the eye, thus e.g. on L_b , L_s and L_y , but also on the location within the field of view, etcetera (2.33).

The orthogonal grid display is very well suited to coding schemes wherein the x and y directions are preferred orientations such as block diagrams, text and tables; for oblique angles the combined effects of sampling and pixelform causes raggedness at edges. This phenomenon tends to increase the contrast increment threshold of small spots in grey-tone images. Also, the gradual desensitization for the apparent periodicity in the display surface may induce a masking effect of patterns with the same periodicity even though the spatial frequency content is very different (2.5), (5.13). The periodic components of the grid can be attenuated by using covers with optical filter characteristics; the simplest being a low pass filter such as ground glass with controlled blurring property.

Example: for a display located at a viewing distance of 0.7 m (28"), and operated at a max. spatial frequency of e.g. 40 cycles per visual degree where the eye's response, at given luminance, field size, etc., requires an MD = 1 to just perceive the (sinusoidal) grating (2.2.1), the angle one such cycle subtends equals 0.3 mm on the display face. Assuming that the visible part of the face is 100 mm, one can distinguish about 300 cycles or 600 points on one horizontal line.

2.1.5 SPATIAL FREQUENCIES AND TEMPORAL FREQUENCIES

In Europe the frame repetition rate is 25 Hz, in the US: 30 Hz. Such low frame rates cause problems with flicker perception, see 2.2.5, so that each frame is split up into two half frames or fields, displaced by one line with respect to each other (interlaced), such that perceived frame flicker is 50 Hz and 60 Hz respectively. This is alright for TV pictures, but the displacement causes jittery pictures for high contrast horizontal lines, e.g. in small size (5x7, 7x9) alpha-numeric characters, resulting in the "twinkle" effect.

The video bandwidth of a matrix or line scan (CRT) display is proportional to the frame repetition rate and the total (average) number of picture elements (pixels) or written length of all traces on the display face during one frame. For the familiar TV format,

each frame consists of a number of lines, 625 in Europe, 525 in the US. The writing speed in both systems causes the beam of the CRT to traverse the width of the screen and return in ≈ 64 microsec. The spatial frequencies displayed transform into temporal frequencies (video-signal) by the writing speed. For instance, if 600 pixels on a line are traversed in 50 microsec., the corresponding video frequency is 6 MHz.

At such writing speeds and spots sizes, and in worst case (bright day-light) conditions, the resulting (average!) luminance of a CRT rasterscan display is too low for aircraft use unless precautions are taken. Therefore, many aircraft CRT displays are used in the stroke writing mode wherein the beam does not write a full raster, but only the vectors required during each frame. Consequently, since face area utilization in this mode is only a small fraction ($\ll 10\%$), the total written length of the traces per field is smaller and thus the video bandwidth. However, to obtain sharp angles between vectors the CRT deflection current amplifiers must be able to supply high currents during short intervals, which is equivalent to strong high frequency video components. These components are not frame rate dependent, so that this rate can be increased to improve the luminance of the trace and thereby to obtain a higher contrast in worst case conditions. The problems of attainable luminance are aggravated with hybrid use of the CRT, where continuous images and alpha-numeric symbols must be superimposed and remain independently legible. Further, vibration will cause blur which is similar to contrast degradation. Experience with present monochromatics shows that with collimated displays, such rasterscan displays are feasible (lecture 4). Present HUD developments have shown that wash-out does not occur and that the eye adapts quickly, while lateral vibration has not been a problem in collimated presentations.

2.2 HUMAN FACTORS AFFECTING DISPLAY DESIGN AND USE

2.2.1 CONTRAST SENSITIVITY, RESOLUTION

When speaking of eye characteristics (2.6), (2.7) it is important to state the conditions of both eye adaptation and of the field of view. The dark adapted eye (scotopic vision) is, in terms of resolution and sensitivity for luminance and color, different from the eye adapted to bright sunlight (photopic vision): see Fig. 2.7.

The higher luminous sensitivity is physically located (Fig. 2.8) in the rods which sense brightness only. Rods are (almost) absent in the central part of the foveal area, where cones (color sensors) are dominant. The sensor density is highest in the foveal area (about 10^5 per mm^2) decreasing towards the peripheral region. Under photopic conditions, in the central foveal region, the resolution and the color perception are much better than in the parafoveal and peripheral view. Eye characteristics normally are quoted under such viewing conditions and therefore represent the optimally attainable perception. In a cockpit when a single instrument is fixated, most of the remaining instrument panel area falls out-side this superior viewing angle: the cone of sharp viewing is about 2° , which means that a round area of 1 cm radius is seen sharp at the viewing distance of 0.7 m. With conventional instruments, this area encompasses hardly more than the business end of a pointer together with the immediately surrounding part of the dial.

The contrast sensitivity (CS) is, among others, a function of spatial frequency and luminance. Displays are normally read under good contrast and illumination conditions (the experienced luminance controls the adaptation state of the eye), which are far above threshold: supra-threshold (ST) condition. As displays must also be observable under threshold (TH) conditions, the latter is a worst case contrast design guideline; but without automatic contrast and luminance control a light emitting display designed for worst case becomes unreadable at normal and high ambient lighting.

Edges, such as are found in display images, require contrast to be adequately perceived. The eye can be regarded as an optical system. Although very non-linear, one may linearize its response under normalized conditions and thus apply linear notions such as Fourier transform (2.8), (2.9). The contrast sensitivity for achromatic light at moderate luminance levels, measured under threshold conditions, is shown in Fig. 2.6.b. It is measured by presenting sinusoidal or bar gratings of different modulation depths ($MD = CS^{-1}$) and observing at what MD the grating is just noticeable. Supra-threshold sensitivity is measured at higher contrasts in matching experiments, comparing perceived contrast of a sample with that of a reference. Also contrast estimation without a reference: free modulus magnitude estimation, gives surprisingly good results. The curves so obtained with harmonic gratings are shown in Fig. 2.9; the curves for bar gratings have 25% higher CS at high frequencies, diverge at lower frequencies (2.9). In this lecture we are mainly concerned with high frequencies.

It has been shown that, for periodic image structures, the maximum retinal frequency perceived is about 60 cycles per degree (cpd). The contrast sensitivity at contrasts higher than threshold (ST), can be obtained by $C_{ST}(f) = 0.14\{C_A - C_{TH}(f)\}$ (2.11) wherein C_{ST} is perceived contrast at supra-threshold, C_{TH} is perceived contrast at threshold, and C_A is the actual, physically measurable contrast. The expression is valid between 1 and 12 cpd. At display matrix grid frequencies lower than 20 cpd, the third harmonics of the tessellated image become better visible at higher luminances. The reticulated display surface may also show very small magnitude second harmonics due to manufacturing imperfections but at ST level the CS may be very high for this frequency. Consequently one is inclined to design pixel size such that in the viewing distance range of 33 to 70 cm (13" to 28"), the second and higher harmonics of the pixel form have frequencies higher than 60 cpd. The pixel diagonal then must be smaller than 0.2 mm equivalent to 1 minute to arc (compare 2.1.4). An alternate rationale is: one can resolve a displacement of two bars (vernier acuity, Fig. 2.12.b) of only 0.4 minute of arc.

Translating this to display resolution: for a direct view display with sharp edge transitions and seen at 0.7 m distance, the vernier acuity amounts to relative displacements of $\frac{0.4}{57.60} \cdot 0.7 \text{ m} = 0.08 \text{ mm}$. Consequently, the limit of resolution is 1200 pixels on a line across a 100 mm wide display, which is twice the resolution calculated for harmonic gratings at moderate light levels (section 2.1.4). Of course, insufficient resolution invites a decrease in viewing distance (by leaning forward).

Under TH conditions the contrast sensitivity is much lower: higher contrasts are required to maintain just noticeable difference levels. Also the contrast sensitivity curve shifts to lower frequencies at lower luminances. The CS_{TH} appears a bit color dependent at the high frequency end. For harmonic gratings it reaches a maximum for spatial frequencies of 3 to 4 cycles per (retinal) degree (cpd). This peak is less pronounced for bar gratings. The power spectral density of the transform of a contrast edge which subtends an angle of ϕ degrees is largely concentrated in the range of zero to ϕ^{-1} cycles per degree. In terms of display resolution the experience of the sharpness of the edge is different depending whether ϕ^{-1} is lower than 3 cycles per degree or much higher. In the first case, the sensations due to higher spatial frequencies are stronger relative to the lower ones, with the result that the perception of the sharpness of the edge is enhanced; whereas in the second all higher components are attenuated relative to the lower ones: thus contributing less to the experienced sharpness. See Fig. 2.10, which shows the mollified perception (c) of the sharp line (a) through attenuation of high frequency components of its spectrum (b). It can be argued that the contrast in the high frequency region should be controlled for good legibility: the blurring effect at low luminance is stronger for letters which have PSD's with the power mostly concentrated in the high frequency region (such as the letter E) (2.31).

The above is in agreement with ergonomic experiments (2.12, 13, 14) in which it has been determined that at normal ambient lighting and high contrast the performance score of letter identification increases with the number of scan lines per letter height (diminishing aliasing error), saturating at 16 to 20 (2.12, 21.16). With the pixel diagonal of 0.2 mm, the pixel frequency becomes 7 per mm so that 20 pixels high letters are 2.8 mm: close to the recommended size of noncritical markings and critical fixed legends, numerals on fixed scales etc. However the cost in pixels per letter is much higher than with the now current Huddleston and Lincoln-Mitre fonts and a breakthrough in matrix display technology is required to attain this desired image quality

2.2.2 VISUAL ACUITY

A graphic display depicts lines and symbols. For the description of viewing thresholds of such images the concept of visual acuity VA (separability of local edges in minutes⁻¹ of arc, gap resolution), is better suited than contrast sensitivity of harmonic gratings. Visual acuity is, just like CS, a function of contrast and luminance level.

For static images, the static visual acuity (SVA) (vernier acuity, resolving two slightly displaced lines) at a fixation point is 0.1 mrad (0.4') under photopic conditions (2.15), p 42-56), (2.16, p 92-95). This is better by about 2 to 3 times than the average diameter of a cone in the fovea. It is measured at maximum contrast, black and white background. When predetermined information is available, even smaller deviations can be resolved: the healthy young eye detects a 2" angular deviation from a straight line (vernier acuity). It stands to reason that the dynamic acuity, where the eye must follow a feature in the image, is lower: e.g. at 1 rad sec⁻¹ angular velocity acuity is 60% of normal, at 2.5 rad sec⁻¹ it is 20% (2.17, 2.18). The static visual acuity decreases gradually with retinal angle as depicted in Fig. 2.11.a. It is impaired by bright light sources of reflections located within 1 rad (60°) of the point of regard.

The above numbers are valid for comfortable viewing conditions, and change with attainable focal accommodation. The combination of cornea and eye lens of a healthy young eye have a strength which can be varied between 60 and 70 diopters. The focal range is

then from 0.1 m to infinity, the focal accommodation time being about 0.6 sec (2.9) from near to far. This capacity, and the SVA, deteriorate with age, see Fig. 2.11.b, (2.17, p 112). Color perception has lower resolution than luminance perception (about 3 x) (2.16, pp 135-141) (2.12). Also the color aberration of the eye optical system results in smaller resolving power. Thus the subtense under which a color display is seen must be larger than for black and white (under optimal viewing conditions).

2.2.3 SCANNING OF THE IMAGE

A much larger area of the image than subtended by the fovea is seen sharp because the image is visually sampled by saccadic movements of the eyeball: these rotational motions are highly correlated with the attention value of features in the image. A saccade of 20 degrees takes about 70 msec, a small saccade ($< 1^\circ$) 20 msec (2.18). It is impossible to keep the eyeball steady for prolonged time: saccades occur within periods of 200 msec to 1 sec. Visual pursuit of a moving or vibrating object is possible by rotation of the eyeball provided its angular velocity remains lower than 5 rad sec^{-1} . A concentrated look for at least 200 msec at a specific feature is called a fixation. When scanning an image, one requires a fixation of about 200 msec to accept or reject a feature; one saccade for jumps up to 20 degrees, two for features wider apart.

For reading the indicated value, a redirection, refocus, fixation and response time are involved, together from between 0.4 to about 2 sec. (2.15), (2.16), (2.20). The time required is smaller when the display/pointer position has not changed since the previous reading, thus can be remembered and quickly recognized. However, doing so requires that one can aim the direction of view with an a priori accuracy of about 2° ; a value which is confirmed by experiment (2.18).

Normal pointing angles of the eye without additional head movement are about $+ 25^\circ$ (up), $- 35^\circ$ (down) and $\pm 15^\circ$ sideways (2.19), (2.20). In the area bounded by these limits the optimum viewing characteristics (foveal) can be utilized for primary display instruments. For concurrent indications (fixed head) the parafoveal area, subtended by 12° extra, can be added; at 0.7 m viewing distance leading to the viewing area of Fig. 2.12. Indicators which should often be scanned, must lie in such an area centered around the major direction of view, while indicators which must be seen irrespective of head movement may be advantageously helmet mounted.

Indicators which of necessity must be mounted outside this viewing area ($\pm 30^\circ$ from operator's line of sight) should be scanned less frequently; thus, for comparable attention value with fixed head orientation, they must be larger and must not rely on intricate symbol forms and color, because in peripheral vision the resolution of the eye and its color sensitivity are much degraded.

2.2.4 SPATIAL LUMINANCE VARIATIONS

The eye is sensitive to spatial luminance variations (threshold sizes as function of display contrast) and to temporal luminance variations (blinking, flicker, twinkle sensation) as function of modulation depth. For round, homogeneously illuminated targets Blackwell (2.21) has researched the relation between contrast thresholds vs visual angle (foreground) as a function of eye adaptation. The latter is dependent on display and surround luminance in the cockpit and also on outside viewing conditions (2.16, pp 259-276). Fig. 2.13 shows graphs of these contrast thresholds which depict "worst case" luminance requirements for 50% probability of detection of single dots (pixels). Others also have determined, under varying conditions, the minimum contrast required to resolve two dots or lines. Carel (2.22), (2.2) has adapted Blackwell's results into guidance rules for calculation of display design, useful for performance/cost analysis on a relative basis which may show where there is room for improvement and/or the (in)flexibility of constraints. Based on this work one can model for graphic displays, for comfortable (supra-threshold) viewing and short reaction times, the relation between

the required foreground luminance L_f and background luminance L_b , valid for pixel sizes Δx (in minutes of arc) in the range $1 < \Delta x < 5$:

$$\frac{L_f - L_b}{L_b} = (2.7 + 15 L_b^{-0.67}) (\Delta x_2)^{-2}$$

the factor 2.7 being dominant in the high background luminance range $10^4 - 1 \text{ cd m}^{-2}$, the factor $15 L_b^{-0.67}$ in the low luminance range $1 - 10^{-5} \text{ cd m}^{-2}$; see Table 2.2.

Table 2.2

$L_b [\text{cd m}^{-2}]$	C_{VTH}	$2.7 + 15 L_b^{-0.67}$	$L_f (\Delta x_2 = 1) \text{ cd m}^{-2}$
$(10.000)^{-1}$	450	7200	0.7
$(1.000)^{-1}$	120	1500	1.5
$(100)^{-1}$	20	330	3.3
10^{-1}	3.2	73	7.4
1	0.9	18	19
10	0.42	5.9	70
100	0.22	3.4	440
1000	0.18	2.9	3.900
10.000	0.16	2.7	37.000

The expression describes the desired supra-threshold contrast also determines the modulation of the driving voltage u of the pixel. Assume a driving characteristic $L = C_1 \cdot u^\gamma$, then $\Delta L/L = \gamma \cdot \Delta u/u$. Let the luminance of the driven pixel be $L_f = L_p + L_b$ so that $L_p = L_f - L_b$; of the non-addressed pixel L_b - the emitted light flux is just about zero, u_b its associated bias voltage. Thus $L_p = \Delta L$ and the relation becomes

$$\frac{\Delta L}{L} = \frac{L_p}{L_b} = \gamma \frac{\Delta u}{u} = (2.7 + 15 L_b^{-0.67}) (\Delta x_2)^{-2}$$

For a pixel size of 1 minute of arc, over the luminance range of photopic view ($L > 3 \text{ cd m}^{-2}$), the driving voltage Δu can be proportional to u_b provided the display $\gamma = 2.7$ and the background driving voltage u_b is proportional to L_b .

In the foregoing nothing has been said about the use of non-uniform diffusers. However, some reflecting surfaces do emit a fraction in the form of specular reflection; e.g. some Liquid Crystal Displays, also the L_b of a CRT is partly specular. Light emitting diodes (LED) and certain contrast enhancing covers are non-lambertian radiators. It should be possible to design the total geometry to make use of the non-lambertian distribution by pointing "lobes" toward the user of the display. Otherwise, the consequence is that the contrast becomes dependent upon the angle of inclination of the display surface with the line of sight, which restricts the viewing angle and forces the design towards a worst case rating.

2.2.5 TEMPORAL LUMINANCE VARIATIONS (FLICKER)

The perception of temporal luminance variations depends among others on the flicker frequency, the luminance, the size (retinal angle) of the flickering field and on the viewing angle (2.24), (2.25). In Fig. 2.14 the critical fusion frequency (CFF) is shown for which the sensation of luminance variation is just not noticeable at lower modulation depth. For the area under the curve, the modulation is perceived. This curve depends on the average luminance level, and is measured under photopic conditions in the central (foveal) region, for a disc size compatible with the maximum contrast sensitivity (Fig. 2.6.b). For smaller flickering fields the required modulation depths are higher

The flicker sensitivity of the eye is lower in peripheral view directions, because the receptor density is lower. Yet, the irritation due to flickering off-axis displays can be worse. Few simple, conclusive, engineering data exist about avoiding the detrimental effect of flicker sensitivity in peripheral view, with stimulation from many directions and different solid angles, as experienced in front of large area instrument panels like in a cockpit using mixed technologies.

2.2.6 LEGIBILITY

The criterion for legibility is not constant brightness difference but satisfaction of visual cognition.

It is a complex notion, operationally defined as composed of the elements:

- symbol reading error
 - word reading error
 - average fixation time
 - allowable thresholds of such operational inputs as: display illumination, surround luminance, structural characteristics of (and ratio between) diffuse and specular reflections, viewing distance and angle, eye accommodation and (various sources of) blur, (momentary) luminance adaptation level of the eye.
- There are some very complex interactions between the input factors and legibility, see Fig. 2.15. Experience obtained through research for the book printing profession taught that such functions can experimentally be optimized (2.12), (2.14), (2.16) using notions such as
- font: basic geometry and "style" of a set of (alpha-numeric) characters;
 - stroke width-to-height ratio or relative active area: the proportion of a symbol which actually emits or reflects light (important in dot-matrix representation);
 - symbol width-to-height ratio;
 - symbol spacing: important to the perception of word-Gestalt;
 - size of the alphabet: number of characters with maximally different features, including sub- and superscripts;
 - size of the wordset and the "feature distance" between words.

The symbol height determines the subtense under which the symbol is seen at a given viewing distance. Legibility is different for given symbol subtense under varying conditions of luminance, contrast, blur, resolution and technology. For instance, for raster scan and dot-matrix displays, symbol subtense must be larger for coarsely quantized symbols (6 lines/symbol \rightarrow 36 minutes of arc, 12 lines/symbol \rightarrow 15 minutes of arc) (2.12).

Symbol quantization is another important parameter. For the restricted range of symbols such as the decimal numbers, the seven bar display is satisfactory. For the range of alpha-numeric symbols the lower limit for symbol quantization is the 5 x 7 matrix. This yields just acceptable error performance under favourable reading conditions and at maximum visual resolution (see section 2.2.1).

Also involved is the parameter in Fig. 2.15 which is not objectively measurable, namely "font". Several designs made specifically for computer generated characters have been proposed (2.14), (2.26). The measurement of their effectiveness is part of human factors methodology. For matrix displays with an orthogonal grid supporting non-rotatable alpha- numerics the modified "Huddleston" font presently appears optimal for the 5 x 7 character block; the "Lincoln Mitre" font for 7 x 9 and larger. However, this optimum with respect to other fonts fortunately is rather flat. When the symbols must "withstand" rotation such as in an ADI, the size of the character block must be at least 11 x 14 pixels to avoid excessive distortions of the symbols as they remain locked to the grid. This effect is less severe in the case of stroke-written symbols (only the end points of the strokes written by the vector generator are locked to the grid), because a higher effective resolution is obtained. This technique is, however, limited to basically analogue applications such as are possible in CRT displays.

Correct symbol spacing aids the recognizability of words. Most of the data available on this topic were collected for non-electronic display media. Values ranging from 25-200 percent of symbol width are acceptable, with 50% a good middle value (2.12).

Percent active area is important for displays with a uniform luminance technology, e.g. reflective type displays, electro-luminescence (EL). The larger the area the more light output per dot, which benefits the legibility (2.27). However, at constant luminous flux (e.g. LED's) the luminance varies inversely proportional with area, so that contrast increases with smaller active area. Provided the resolution requirements of the eye are met, for LED type dot-matrix displays small active area per dot or pixel is proven to be the more economical way to increase legibility (2.28). An added physical advantage is that the power efficiency of the LED improves at subresolution size.

The variation of contrast as a function of viewing angle (LCD, LED mechanisms) is highly dependent on the type of technology. Usually such data are available. For viewing angles smaller than 30° the foreshortening of symbol width or height does not impair the legibility (2.12).

2.2.7 ENVIRONMENTAL EFFECTS ON LEGIBILITY

When a direct view display is vibrated with respect to the eyes, three effects are possible which may cause deterioration of the legibility.

Firstly, the commonly experienced phenomenon in continuously (not intermittently) energized displays is, that the contrast of edges perpendicular to the sense of vibration become blurred. The reading error depends on the frequency of vibration; at low frequencies the legibility remains acceptable for the larger sizes of symbols (2.29).

Secondly, the effect associated with the periodically refreshed (flickering) type of display, with a frame rate higher than the fusion frequency and with moderate to long persistence contrast or luminance (e.g. LCD, CRT). For large excursions in retinal angle (such as rolling head of the pilot) multiple complete images are seen superimposed.

Thirdly, in matrix displays with short persistence pixels (LED, DC plasma and EL) which are e.g. horizontally scanned and strongly vibrated vertically, the scanned lines appear to break up to the extent that text and numbers become incomprehensible.

Collimated displays are much more tolerant to vibration (2.30).

Condensation, dust etc. may cause blur, but the display legibility must remain "sufficient". Blur degrades resolution and causes the MTF (Fig. 2.6.a) to fall off more at the higher spatial frequencies. Consequently, the symbol identification must not rely on high resolution (2.31). Assuming that symbol subtense is large enough to permit good legibility, actual practice has shown that 10 pixels/symbol height (14 for TV) (2.12), (2.26), are desirable (16 to 20 with requirement for subscript and superscript).

2.3 COLOR IN DISPLAYS

2.3.1 THE VALUE OF COLOR IN DISPLAYS

The use of color in display technology (2.16), (2.32), (2.33) is mainly for coding purposes, to improve perception by adding color contrast to luminance contrast. As such, the notion of just noticeable differences (JND) is more important than the notions used to describe the color sensation proper. However, one cannot very well describe the mechanisms involved without properly defining the psychological concepts of perceived color (2.6), (2.34).

Achromatic color perception is defined as one not possessing a hue. Hue is the attribute of a color perception denoted by red, yellow, green and so on: the degree of saturation being the "difference" between the perceived color and the achromatic color perception most resembling it. Brightness sensation is caused by the perceived luminance of a luminous source, independent of its color. Chromaticness of a color is determined by the attributes hue and saturation.

Perceived color cannot be measured objectively. For instance, the perceived color depends on the eye's adaptation state which, among others, is influenced by the dominant color preceding the color stimulus and by the prevailing color of the surround (2.35). Even under ideal conditions a specific color sensation Q can be induced by radiant fluxes with different spectral distributions (metameric colors). With the eye adapted to other than ideal conditions, these metameric colors can be perceived with differing hues and saturation. Similar effects are possible with isomeric (identical spectral distributions) colors. An example of simultaneous color contrast induction is the perceived color (hue) of e.g. a green line which extends into both brown and blue backgrounds such as may be realized in an electronic ADI: in order to maintain the same hue along the line the objective color (as measured with a spectra radiometer) must be changed at the intersection with the two backgrounds. Another example is that certain colors change hue with luminance and with ambient (surround) illumination (2.6), (2.36); conversely the detection thresholds at low light levels are also color dependent, but in a different way. Such dependences can be measured and tabulated objectively in a statistical sense, but may vary considerably from person to person.

The color vision properties of the eye are different for very dim, low light level scenery (scotopic vision) as compared to the other extreme, high intensity, high contrast luminances. Most experiments with eye response to color were carried out at comfortable luminances; however, especially in the last two decades much attention is given to the extrema. At very low light levels, the general threshold (luminance) and the specific threshold (hue) coincide for red, are different for other hues: colorless interval (2.37). Red is the most saturated hue, greenish-yellow (520-580 nm) the least (2.32), (2.37).

For a 2° field, under photopic conditions, the JND are given in Fig. 2.16 where it is shown that e.g. the blue-green and the yellow JND thresholds are lower than the red JND threshold (2.38). This determines the tolerances in the driving signals of a CRT display, and in the homogeneity of color selective filters, etc. Experiments with very high surround luminances (2.28), (2.39) have indicated that hue wash-out occurs easily for yellow, followed by green and blue, and is the least for red.

Under varying illumination, degree of saturation is a poor code. In addition, it was found (2.40) that very saturated colors, used in low to normal surround luminance conditions, induce fatigue and must be avoided. Because brightness coding also affords low resolution (2.16, p 112) color coding mainly must be limited to selections and combinations of hues; form coding remaining the most versatile (size, shape, orientation, alpha-numerics). The use of hue, for a 100% identifiability under worst case conditions, is also restricted to e.g. 4 by (low level) threshold and (high

level) wash-out effects, by accommodation difficulties of the average healthy eye and by the existence of certain color anomalies (2.6, pp 154-168). The increase (through color coding) of the set of 100% identifiable symbols in practice seems limited to a factor of about 2, but in many cases the search and reaction times are much shorter and a better mental picture is obtained (2.32-33), (2.15-17). Presently the value of color is insufficiently researched, although there is some tradition in colored mechanical displays (ADI, map displays). There appears to be a strong user preference for color, as evidenced by developments for Airbus and 757; but one cannot make predictions on the cost effectiveness in terms of coding quality and perception efficiency.

2.3.2 COLOR CHARACTERISTICS OF DISPLAYS

The results of numerous color coding experiments are not always comparable nor directly applicable. Some were obtained in trials with colored reflecting surfaces, others with colored light projected onto a diffusely reflecting surface, others with light emitting symbols. However, they make use of the same psycho-physical concepts (2.6), (2.34) which are objectively measurable. In the following these concepts and their interrelations are briefly introduced and defined where applicable to the field of displays.

Monochromatic color: an electro-magnetic wave $\vec{Q}(\lambda)$, its radiated energy located at wavelength λ and confined to a small band $\Delta\lambda$ around λ . The luminosity interval (p. 2.2) is bounded by $400 < \lambda < 750$ in nm. The color of any luminous flux \vec{Q} can be matched by the additive mixture of three suitable monochromatic base colors, R, G and B: its representation in three dimensional color space given by (Fig. 2.17)

$$\vec{Q} = R \cdot \vec{R} + G \cdot \vec{G} + B \cdot \vec{B}.$$

The equality is obtained by an experimental color and luminance matching operation. \vec{R} , \vec{G} and \vec{B} are the spectral primary colors; customarily chosen so that equal amounts produce an achromatic color sensation (white, equal energy spectrum). The wavelengths of R, G and B have been standardized in 1931 by the Commission Internationale de l'Eclairage (CIE, ICI): their spectral locations are: R at 700 nm (red), G at 546.1 nm (green) and B at 435.8 nm (blue). The scalars R, G and B are the tristimulus values of the color \vec{Q} in the system R, G, B; their sum being the total luminous flux (in lumen if $|R| = |G| = |B| = 1$ lumen), their ratios representative of the perceived color. For instance: the tristimulus values of a color \vec{Q} are R, G and B when the color and luminance of \vec{Q} cannot be distinguished from the color and luminance of the additive mixture of R lumen R, G lumen G and B lumen B. Chromaticity is the point Q located at the intersection of the vector \vec{Q} with the unit plane determined by $R + G + B = 1$ (the chromaticity diagram) in three dimensional color space). The chromaticity coordinates of Q are $r = \frac{R}{R+G+B}$, $g = \frac{G}{R+G+B}$, $b = \frac{B}{R+G+B}$ with $r + g + b = 1$ independent of the luminous flux of Q.

Most colors are not monochromatic, but their luminous fluxes $\vec{F}(\lambda)$ have power spectral density distributions $P(\lambda)d\lambda$ (Fig. 2.1). The resulting color \vec{Q} is considered as the additive mixture of monochromatic colors $\vec{Q}(\lambda)d\lambda$ with tristimulus values $R(\lambda)d\lambda$, $G(\lambda)d\lambda$ and $B(\lambda)d\lambda$. Thus the color $\vec{Q} = \int \vec{Q}(\lambda)d\lambda$ has the tristimulus values $R = \int R(\lambda)d\lambda$, $G = \int G(\lambda)d\lambda$ and $B = \int B(\lambda)d\lambda$. The radiant power contribution of $\vec{Q}(\lambda)d\lambda$ is $P(\lambda)d\lambda$; its chromaticity coordinates are $r(\lambda)$, $g(\lambda)$, $b(\lambda)$ obtained analogous to r, g, b of Q. Consequently $R = \int P(\lambda) \cdot r(\lambda)d\lambda$, $G = \int P(\lambda) \cdot g(\lambda)d\lambda$ and $B = \int P(\lambda) \cdot b(\lambda)d\lambda$. With this description, the color sensation induced by electromagnetic radiation of known spectral distribution can be predicted. In Fig. 2.18 the functions $R(\lambda)$, $G(\lambda)$ and $B(\lambda)$, depending on the wavelength λ_Q of Q, are depicted for spectrally pure colors Q with luminous flux of 1 lumen ($|Q| = 1$). The fact that $R(\lambda)$ and $G(\lambda)$ are partly negative means that matching is obtained by adding R lumen R and/or G lumen G to the source of Q instead. It follows that with these chosen base vectors not every spectral color can be obtained by an additive mixture, because negative light does not exist.

However, the requirement of negative power for a range of colors is inconvenient for colorimetry: the CIE adopted in 1931 a transformation of the trichromatic system based on R, G and B to one based on new primaries X, Y, Z which are non-real - i.e. they cannot be realized by physical luminous sources and so remain outside the region of actual color vectors in three dimensional color space. The chromaticity coordinates are x, y, z analogous to r, g and b, and since these are dependent ($x + y + z = 1$), the chromaticity of all real colors can be represented in an x, y diagram where all colors have equal luminance. The coordinates x and y determine hue and saturation, see Fig. 2.19. The locus of all spectrally pure (fully saturated) colors remains within the first quadrant. The straight line at the bottom, connecting blue and red is the purple line which borders non-spectral colors. See also Fig. 2.21.

A straight line connecting any two points P, R within the triangle determines the hue and saturation of the color Q obtained by the additive mixture of light sources with the chromaticity coordinates of the endpoints P and R. The equal energy stimulus E is located at $(\frac{1}{3}, \frac{1}{3})$ and represents an achromatic color (white, grey). A standard CIE white source C lies close to E. Within the color triangle, the relative distance $\frac{QC}{SC}$ between any point Q to the achromatic point represents the degree of saturation. The intersection S with the spectral locus of the line, connecting the chromaticity point Q of a color with that of C, determines the wavelength of the dominant color of Q. Its intersection T with the spectral locus in the opposite direction determines the complementary color. Color measurements are covered in e.g. 2.34.

Experiments have shown that the just noticeable differences (JND) in chromaticness are in the x, y diagram given by ellipses which differ greatly in size, depending on their position. Suggestions were made, therefore, to transform this diagram such that the JND ellipses would become approximately equal. This UCS (for Uniform Chromaticity Scale) diagram (Fig. 2.20), with the coordinates u, v was adopted by the CIE in 1960. In this figure the colors obtainable with a shadow mask color CRT (triangle RGB) are depicted. The chromaticity diagram is regularly refined (e.g. the 1976, CIE-UCS system in which the "ellipses" have a more circular shape). The UCS diagram is now commonly used in the specifications of color displays and in experiments concerning the effectiveness of color in displays.

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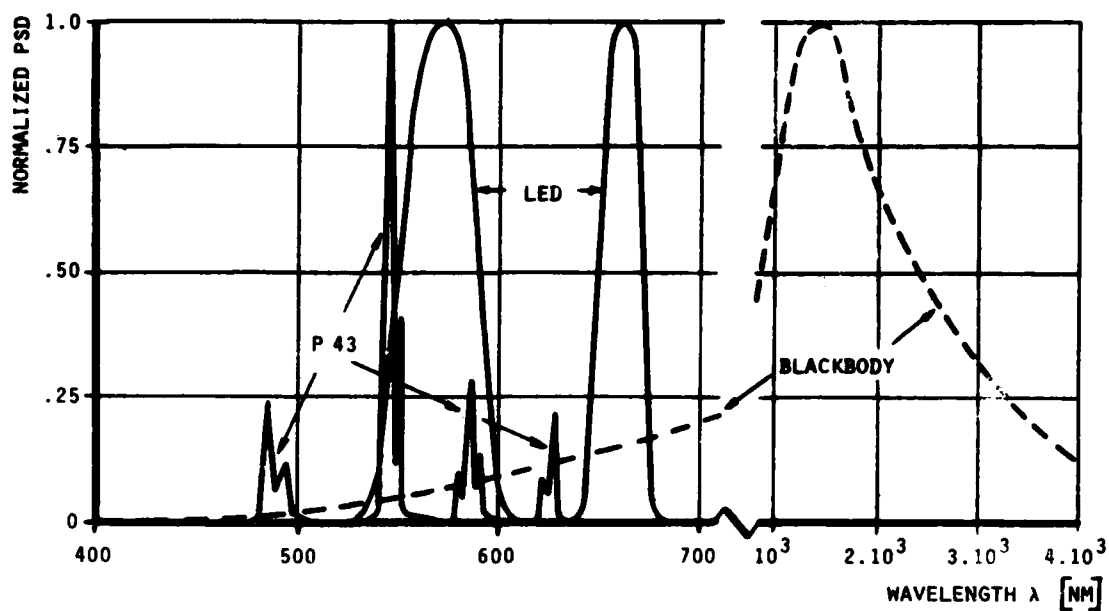


Fig.1 Power spectral densities (PSD) of three types of radiators

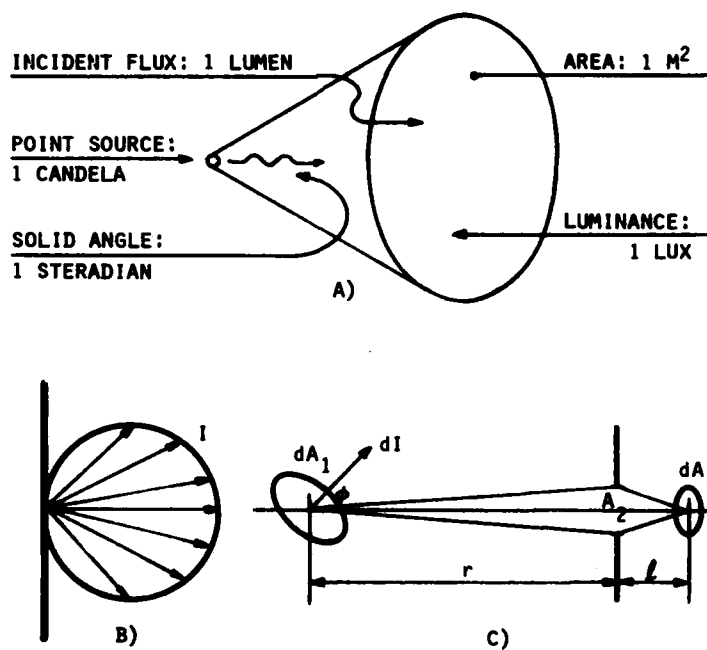


Fig.2 Illustrations to the definitions of Section 2.1.1

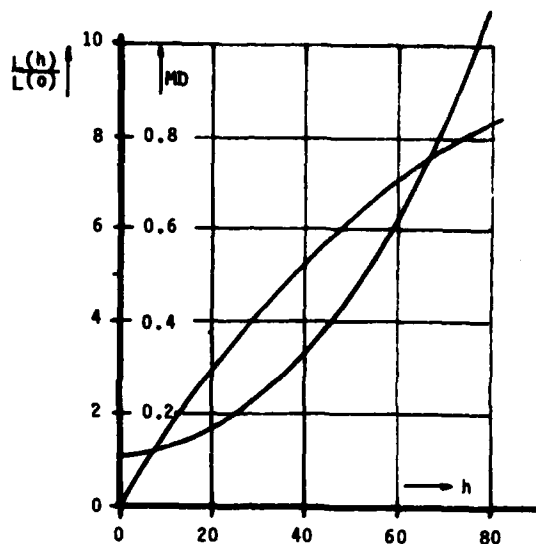


Fig.3 (Exponential) luminance function for constant contrast stepsize;
associated modulation depths

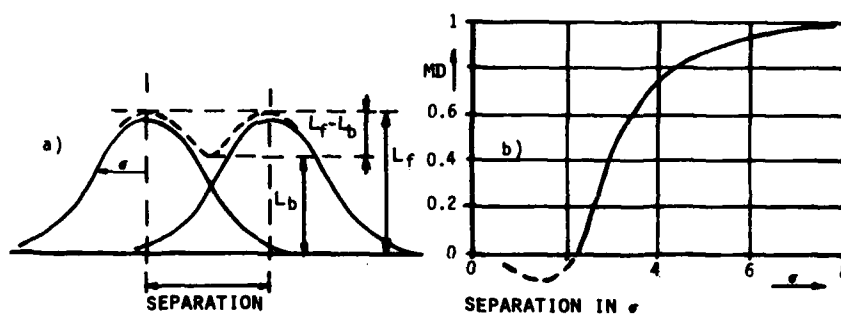
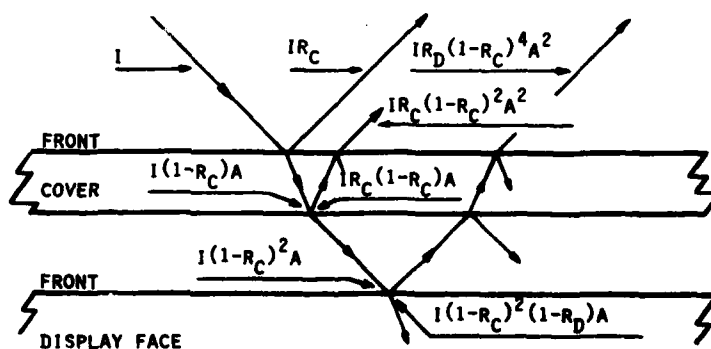


Fig.4 Overlapping PSF's causing decreased MD at low line separation



I : INTENSITY OF EXTERNAL LIGHT.
 R_c : REFLECTION COEFFICIENT OF COVER MATERIAL.
 R_d : REFLECTION COEFFICIENT OF DISPLAY FRONT.
 A : ATTENUATION FACTOR OF COVER.

Fig.5 Transmission and reflection in contrast enhancing cover.
 R_c , R_d : reflection coefficient, A : attenuation coefficient

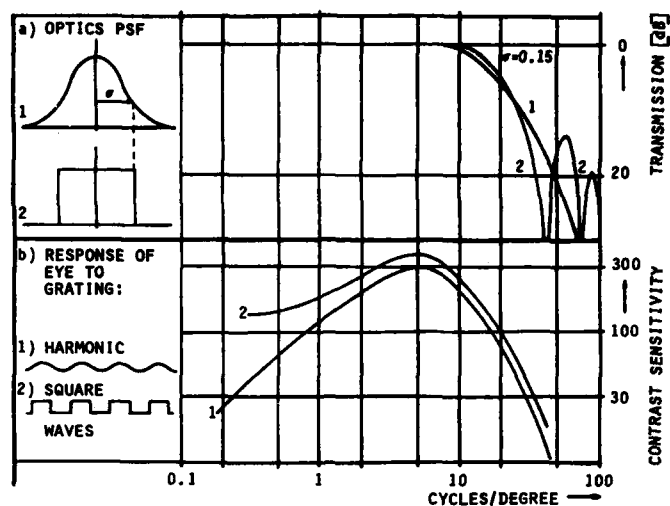


Fig.6 (a) CRT spot and matrix pixel luminance density distributions with their Fourier transforms.
(b) Modulation transfer function of the average photopic human eye

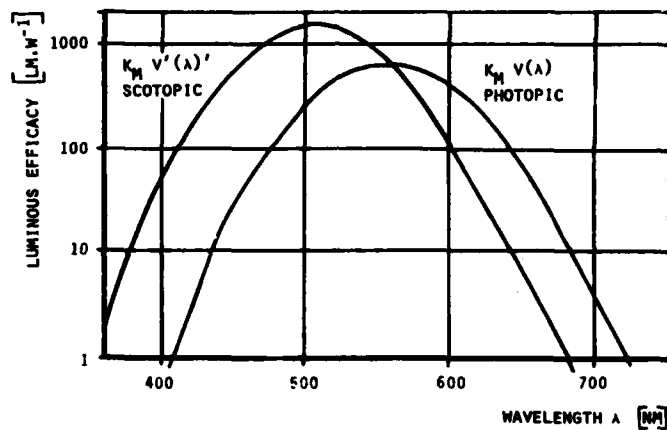


Fig.7 Luminous efficacy $K_m V(\lambda)$ or $K'_m V'(\lambda)$ of the human eye

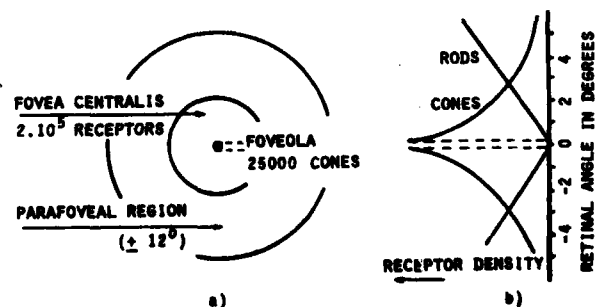


Fig.8 Retinal regions (a) density; (b) distributions of cones and rods

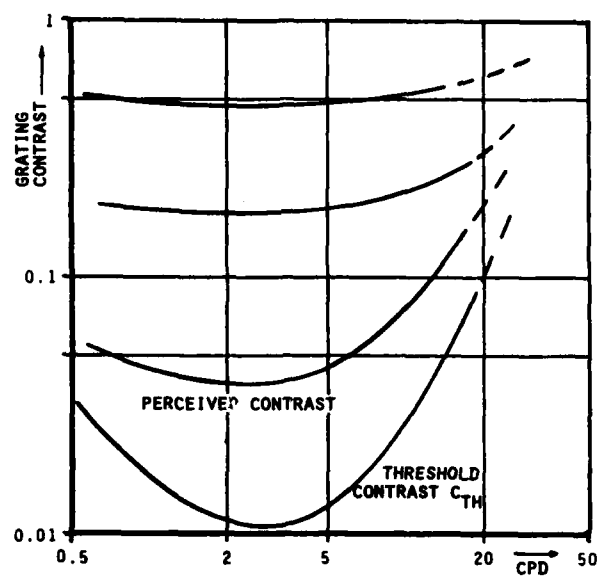


Fig.9 Perceived contrast over acutal contrast under suprathreshold conditions

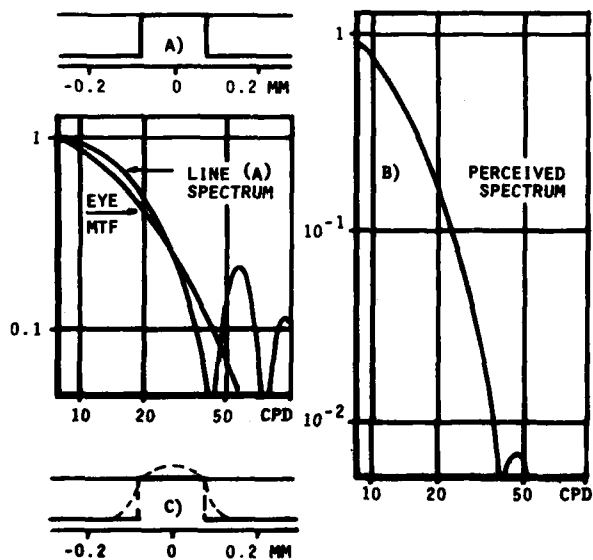


Fig.10 Mollified perception (c) of line with sharp edges (a) through attenuation of spatial high frequency components (b) on its spectrum (a) by the MTF of the eye

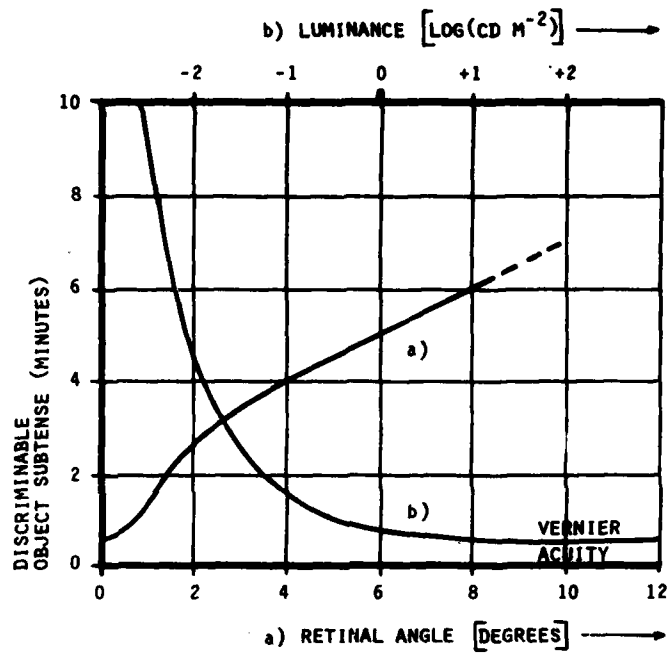


Fig.11 Static visual acuity: (a) as a function of the distance from the centre of the fovea;
(b) as a function of luminance, for foveal view. Both at 100% contrast (C_v)

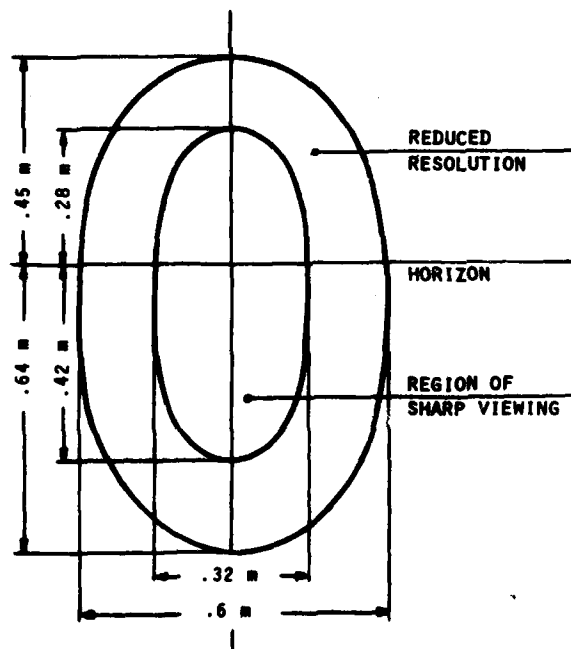


Fig.12 Viewing area, at 0.7 m viewing distance, covered with eye movements only

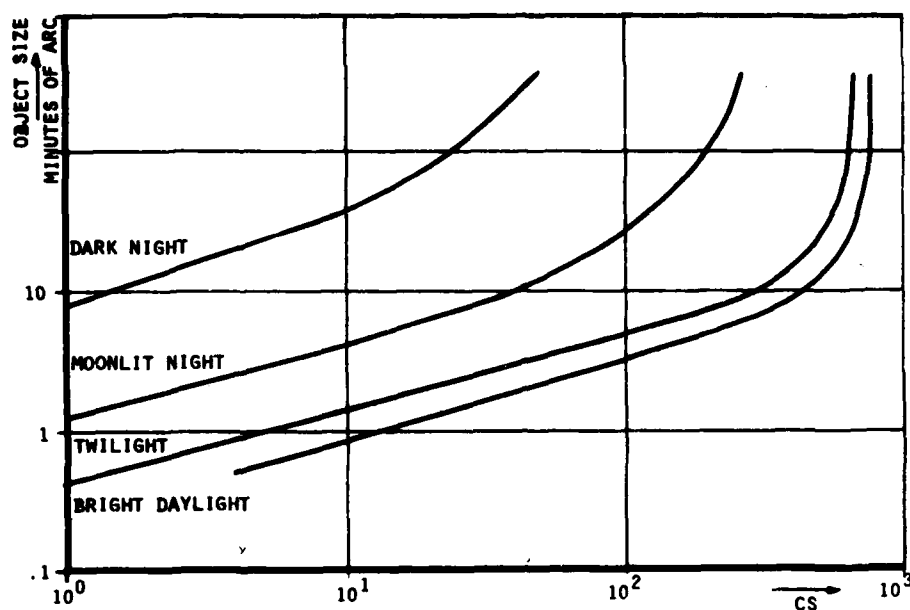


Fig.13 Contrast threshold vs visual angle at four adaptation levels, of the average human eye

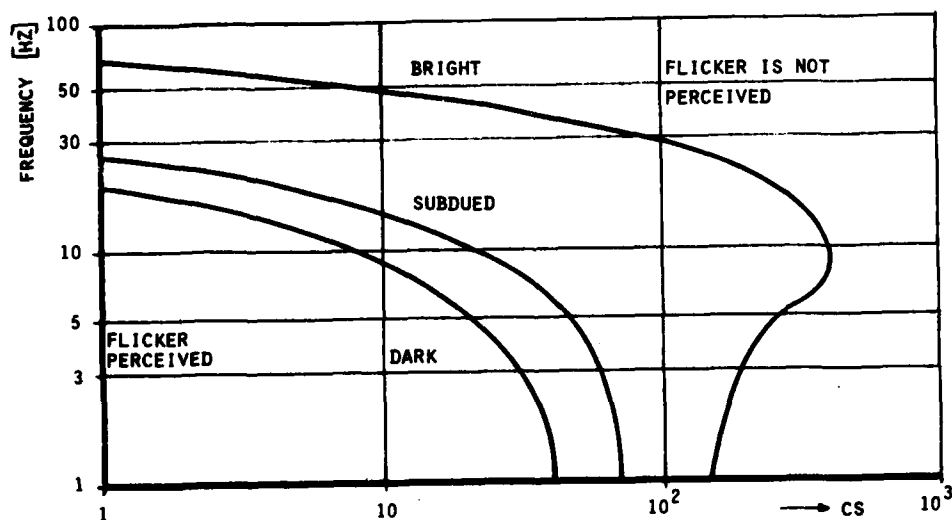


Fig.14 Curves of apparent flicker fusion of a small flickering field in a large, constant, background; at three levels of brightness

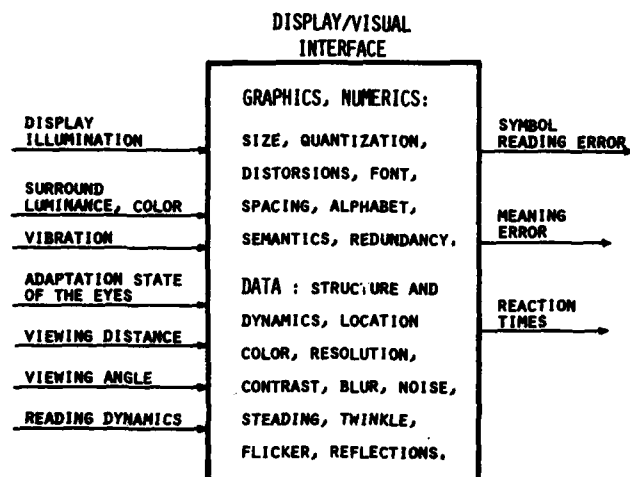


Fig.15 Legibility performance factors

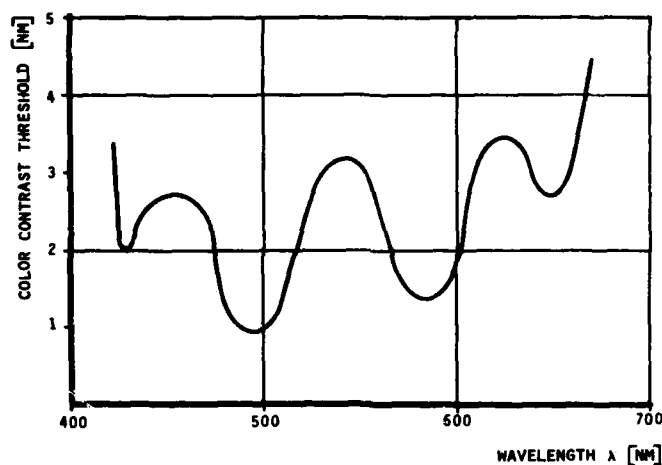


Fig.16 Wavelength discrimination (JND) detected as different hue, under specified conditions

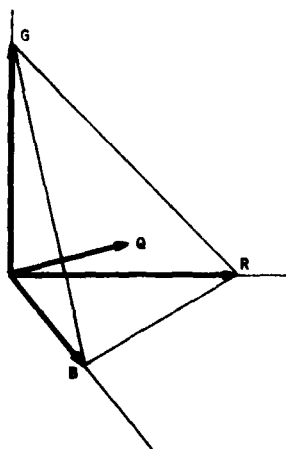


Fig.17 R, G, B color space

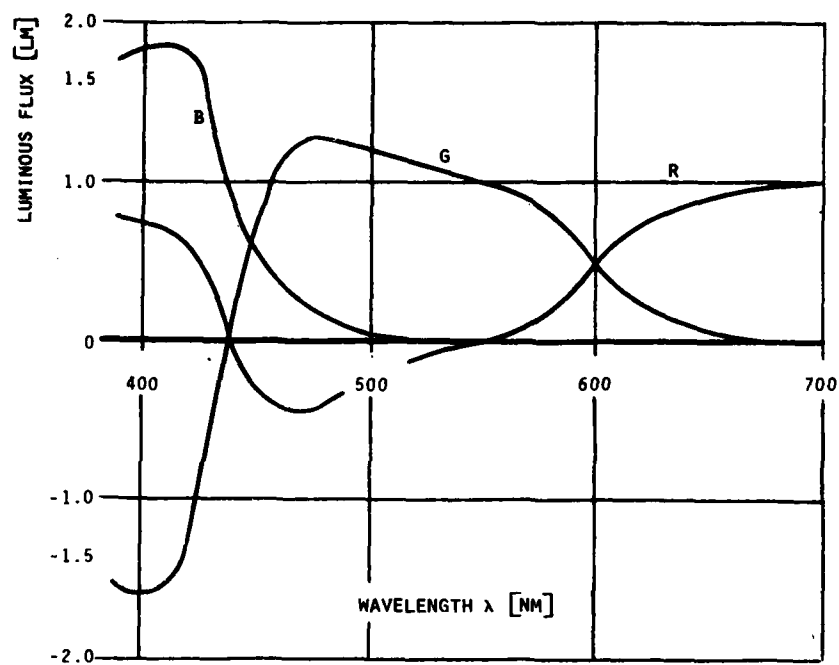


Fig.18 Tristimulus values of spectral colors in normalized R, G, B system

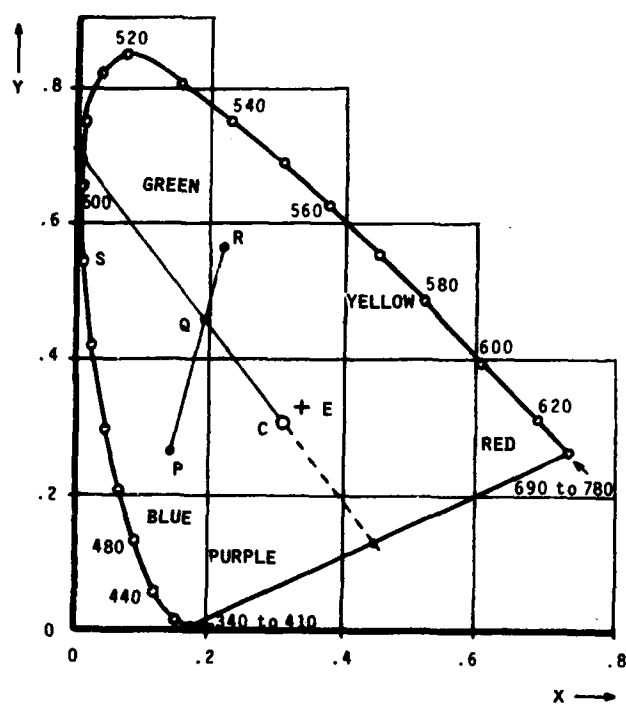


Fig.19 CEL, x, y chromaticity diagram

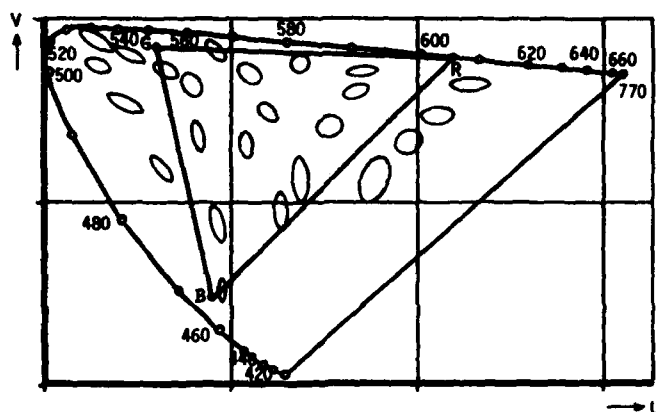


Fig. 20 CIE/UCS diagram showing JND (McAdam) ellipses (10 x actual size).
The triangle RGB represents addressable hues of a shadow mask CRT

1931 CIE CHROMATICITY DIAGRAM WITH

--- : HUE AREAS

— : ISO SENSITIVITY CURVES OF THE EYE [2.41]

TRIANGLE : ADDRESSABLE CHROMATICITIES OF P₂₂ COLOR PHOSPHORS

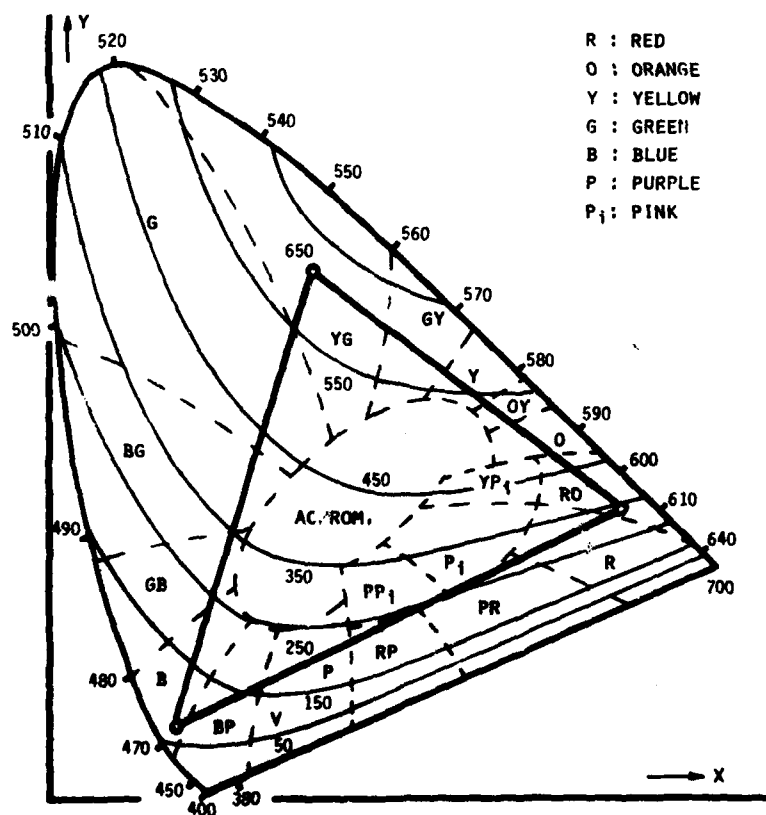


Fig. 21 Chromaticity diagram; distribution of hue fields and addressable colors of P₂₂ phosphors based CRT

COCKPIT ENVIRONMENT

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SUMMARY

A description is given of the cockpit environment where modern display technology is applied. Six display devices are discussed. Applications are classified according to their visualization format.

INTRODUCTION

The cockpit is where the pilot and crew interact with the complex systems used to accomplish the mission of an aircraft. The role of a cockpit display is to provide a visual communications link between a piece of aircraft equipment and its human operator. For the link to be effective it is necessary that the information flow from the equipment to the display and also from the display to the human operator allowing him to take timely action based on the information. Each individual display requires the operator's attention which has to be time-shared with the other displays and with other tasks. This section will be devoted to a description of the environment where this visual communications link is intended to function. It will describe briefly the make-up of current cockpits and classify displays by their specific application.

PILOT PERSPECTIVE

What is it like inside the cockpit of an aircraft on a military mission? While there are variations which depend upon aircraft type, altitude, time of day, etc., there are also typical characteristics. First, it will probably be cramped. The pilot is belted to his seat wearing helmet and gloves. The helmet is worn to protect his head. It contains earphones and microphone for oral communication plus clear or sun-shaded visor (or sunglasses) to protect his eyes. For high altitude flight the helmet will be fitted with an oxygen mask. The gloves are used primarily to protect the hands from injury in the event of fire and are normally worn continuously. The pilot's head is close to the canopy to improve his outside view over the nose of the aircraft. He needs to be able to reach all the switches and actuators in the cockpit which means that most of the area is covered with displays and switches or actuators and extends as far as his reach. There is probably noise and vibration. Low altitude turbulence can be severe enough that the hand needs to be steadied in order to take hold of a switch. While the cockpit may have sound attenuation there is still chatter on the radio. The cockpit air conditioning is often noisy. All aircraft will shake to some degree in turbulence while helicopters are prone to continuous vibration as a consequence of the rotating airfoil. Many pilots fly 100% of the time with their visor down to protect their eyes in the event of a bird strike. Pilots may also turn the cockpit lights full bright in daylight to see the instrument panel through the sun-shading of the visor. Conversely,

at night the lights may be dimmed extremely low in order not to interfere with night vision outside the cockpit. Pilots are taught to scan the outside world and the instrument panel in a way which keeps their gaze moving. During formation flight or at low altitudes they want to keep their gaze outside of the cockpit. They would like displayed information that is needed during those situations to be "up front" i.e., at the top of the instrument panel not far from their outside view. Pilots often operate switches by feel, counting clicks so they don't have to look inside the cockpit. During instrument flight conditions if their gaze remains inside the cockpit it continues to move in a scanning pattern across the instruments or displays.

Temperature variations inside the cockpit can be extreme. Before the aircraft is started the cockpit temperature is near the ambient temperature of its surround except that direct sunlight magnified through the canopy can make individual components too hot to touch with the bare hand. Direct sunlight on blacktop parking ramps and runways can also make the ground ambient temperature very high. In flight the heater or air conditioning normally keeps the temperature moderate, however, military missions are not necessarily aborted when the heater or air conditioning fails. Leaks in canopy seals can cause degradation of air conditioning and pressurization to the extent that frost forms on the inside of the windows at high altitude. It is also common to have large temperature gradients at high altitude where parts of the cockpit in shadow are cold while other parts in sunlight are quite warm.

HISTORICAL PERSPECTIVE

Since the cockpit consists primarily of switches and displays, it is appropriate to consider how many there are. Figures 1 and 2 indicate that the numbers of each have exhibited near exponential growth with time until most recently. Some fighter aircraft have accumulated up to 320 switches and more than 70 displays around one crew member. If the trend were to continue, the pilot would be overcome by the number of displays and switches confronting him. The older displays were predominantly dedicated electro-mechanical devices. With the recent introduction of multi-function electronic displays, primarily cathode-ray tubes, into modern cockpits such as the F-18 Hornet (Ref. 16) the number of displays in the cockpit has been drastically reduced. The introduction of multi-function switches will cause similar reductions in the growth of the switch population. The trend away from dedicated, electro-mechanical dials toward electronic displays is revolutionary. The consequence of the revolution for military fighter cockpits can be seen in Figure 3 which shows the crew station layout for the F/A-18. It features a Head-Up Display, an integrated upfront control panel, and three multi-purpose, cathode-ray displays with programmable switches surrounding each display. The revolution extends to large new civil aircraft such as the Boeing 757/767 and Airbus 310/320 as well as smaller General Aviation aircraft. It is probable that no new major aircraft will be built in the future without electronic displays. This rapid transition has been accomplished primarily with cathode-ray tubes, but there is obviously potential for the ultimate application of newer flat-panel technology.

CLASSIFICATIONS

The applications of electronic display technology in military aircraft can be divided into four basic classifications of visualization format. These formats and their definitions are taken from the 1979 Tri Service Airborne Flat Panel Display Technology Report (1). The classifications are listed in order of decreasing complexity as measured by the expected maximum number of picture elements (pixels) they might contain. Although not a perfect guide, the engineering problems of drive and interface design, fabrication, connection, and packaging all increase sharply with the number of picture elements.

Video devices are those characterized by today's raster television where high-data-rate (at least 25 times a second) information is presented in a pictorial form with multiple shades of grey. This would be utilized for display of sensor information such as forward looking infrared (FLIR), low light level television (LLTV), and scan-converted radar. Presently used raster formats of 525, 625, 875 and 1024 lines are considered typical.

Vector-graphic devices are those which present information in both alphanumeric and simple line drawings with typically one or two levels of luminance in addition to the off state. These devices would be utilized for alphanumeric and graphic information from the aircraft, avionic, engine, and ordnance subsystems.

Message devices are those which present alphanumeric information at low-data rates with not more than two levels in addition to the off state. These would be used for caution or warning indicators as well as for general command and control applications. Typical requirements indicate message formats of approximately 20 characters by 15 rows in which each alphanumeric is arranged in a 5 x 7 or 7 x 9 dot matrix configuration.

Discrete data devices are those which present small amounts of alphanumeric or simple graphic information. These devices could be used for small readouts, legends, paragraphs and multifunction key legends.

Specific applications of interest use one or more of the display formats as shown in the matrix on the following page.

HEAD-UP DISPLAYS (HUD)

The HUD is a collimated (focused at infinity), optically projected display designed specifically for airborne use. The HUD combining glass is located between the aircraft windscreen and glare shield and transmits the real-world scene directly while reflecting the display image so that the two superimposed images are viewed simultaneously by the pilot. The optical magnification of the HUD is scaled one to one for symbols which need to match the real world scene. Indications such as pitch angle may be greater than one to one. Because the reflected image is collimated, the angular size and position of symbol cues projected within the display field-of-view remain constant with pilot head motion. The HUD is used to project vector-graphic and video information.

APPLICATION	Visualization		Formats	
	Video Applica- tion	Vector- graphic	Message	Discrete
HEAD-UP DISPLAYS	X	X		
HEAD-DOWN DISPLAYS	X	X		
HELMET-MOUNTED				
SYSTEMS	X	X		
MISSION MANAGEMENT DISPLAYS		X	X	
KEYBOARD DISPLAYS			X	X
ALPHANUMERIC MODULES			X	X
MAXIMUM NUMBER OF PICTURE ELEMENTS	10^6	10^5	10^4	10^3

The primary functions of the HUD are flight guidance and weapon aiming, therefore a high quality optical system is required that can maintain accurate symbol positioning. The HUD is also used to display symbol cues for other mission modes such as take-off, landing, navigation, terrain following and ground collision avoidance. Electro-optical sensor displays such as Forward Looking Infrared (FLIR) can also be presented on the HUD. Figure 4 shows a functional diagram of HUD optics.

The combiner is located between the aircraft windscreen and glare shield with sufficient clearance to minimize secondary reflections from the windscreen. The HUD must clear the pilot's ejection line, usually with a camera mounted in front of the combiner. The HUD can extend beyond the surface of the instrument panel, but it must not obscure the pilot's line-of-sight (LOS) to other surrounding displays and controls or the pilot's "over-the-nose" LOS. These geometric constraints determine the specific optical performance that can be obtained in any particular aircraft installation. A total field of view from 20 to 40 degrees is desirable for fixed wing aircraft. A nominal contrast ratio of 1.2 against a 10^5 lux (10^4 fc) background is required for graphics. Symbol position accuracy of one milliradian over the central 5 degrees of the field-of-view is required. A three times larger resolution per picture element is required throughout the field of view.

Recent advances in holographically formed optical elements enable the construction of combiner elements which have very high (90%) reflectivity over a very narrow band of optical wavelengths. This enables a bright display to be generated while imposing very little attenuation of the outside scene. Narrowband CRT phosphors are available to which the spectral response of the holographic plates are matched. In addition to the

above advantages the angular selectivity of the holographic elements enable compact optical units to be constructed with wide fields of view. Most existing military HUD's are monochromatic. While several hues of color may be desirable color is unlikely if holographics become fashionable. Reference (2) provides an in-depth literature review of 293 publications relating to the HUD for aircraft cockpit application.

HEAD-DOWN DISPLAYS (HDD)

Head-Down Displays are direct view, flexible information format displays having the capability to display both graphic and video information. The Horizontal Situation Display (HSD) and the Vertical Situation Display (VSD) are two classes of HDD that are associated with two specific types of flight information. Reference (3) discusses the use of map displays in high performance aircraft. Reference (4) discusses HDD in military transport aircraft.

The HSD is a flexible information format (i.e., multifunction) display that, at a minimum, displays the heading information portrayed on a conventional electromechanical Horizontal Situation Indicator (HSI). In essence, it has a designated information function, that being the display of information giving aircraft orientation and any related situation information with respect to a position in a plane parallel to the earth's surface. In addition to the heading indication, bearing pointers, distance, and course deviation indications provided by an HSI, the HSD should be able to provide combinations of:

- o Aeronautical charts and/or Electronically Generated Maps
- o Navigation, Target/Drop Zone Identification
- o Electro-Optical and Radar Sensor Video
- o Flight Control Cues
- o Electronic Warfare Information

The VSD is a flexible information format (i.e., a multifunction) display which, as a minimum, displays the attitude information portrayed on an electromechanical Attitude Director Indicator (ADI). The VSD can provide information similar to the HSD but with respect to a plane that is perpendicular to the earth's surface. The orientation of an HUD and HDD in the cockpit are shown in Fig. 5. In the illustration the HDD shows an HSD information format while the HUD shows ADI information.

The requirement for both the number of grey shades and the luminance ratio between adjacent shades on a video display are the subjects of considerable controversy. The reported number of grey shades needed as a minimum to fully satisfy viewer visual requirements varies from five to thirty for fixed daylight viewing conditions, with the luminance ratio which defines a gray shade varying from 1.4 to 2. To the extent practical the number of grey shades in the display should be matched to the number of grey shades in the sensor.

Sensor-video information can be satisfactorily displayed at 4-5 pixels/mm. on a nominal 525 line display. Display sizes are typically in the range 50 mm diagonal to 300 mm diagonal. The main constraint which forces CRT displays to be small is the limited

space in the cockpit. Of less significance is the requirement to provide sufficient luminance to remain legible. It is desirable to maximize the ratio of display active area to the total panel area occupied, subject to the constraints imposed by clutter and the need for light sensors, controls and switches. Conversely, minimum separations between functionally different types of display information and the need for instrument panel structural integrity both suggest limiting the proximity of adjacent displays. Nominally, 10% of the active area linear dimension of the larger of two viewed displays is needed to separate different but related task information. Larger distances are needed to separate information for unrelated tasks.

HELMET MOUNTED SYSTEMS

Helmet Mounted Systems have been used for over ten years but until recently have not been generally accepted. Helmet Mounted Systems are discussed in References (5)-(8). Examples are shown in Figs. 6 and 7.

These systems fall into two related categories: sights and displays. A Helmet Mounted Sight (HMS) is designed to measure the pilot's line of sight to a target in relation to the airframe and to process that information for use in direct control of weapon delivery systems and remote sensors. The Helmet Mounted Display (HMD) provides the crew member with a head-up TV display monitor which is lightweight, low-powered, gives high resolution and can also be used as a sight. In either case the attitude of the helmet must be measured relative to a selected reference frame.

There are, in general use, three systems which are used to measure helmet angle and position. One is optical, one uses infrared and the other is magnetic in operation. For the helmet to operate as a sight it is necessary to have an aiming mark. The simplest possible sight is an illuminated cross or circle whose image is focused at infinity.

The image source can be a graticule illuminated by a miniature lamp or a matrix array of any suitable technology. This image is then projected and collimated by the optics and presented to the eye after reflection from the visor. Latest advances include the use of a diffractive optical element in the visor which both reflects and collimates the image.

Another version removes weight and heat dissipation problems by forming the image remotely and conveying it via a fiber-optic pipe to the combiner. The piping avoids high voltage going to the helmet, however, there has been some difficulty with the flexibility of the fiber-optic pipe.

An advantage in using a matrix display is the flexibility to change the image. In addition to the aiming mark, discrete data such as speed, range, altitude and pressure can be digitally displayed. Also, flashing direction indicators can direct the crew member where to look for a target.

The Helmet Mounted Sight allows the pilot to acquire the line-of-sight to a target outside the normal field-of-view of the Head-up Display. This data is then immediately available

for use by the Weapon Aiming System or to update the Navigation system by spotting waypoints.

In addition, both slewable weapons and sensors can be slaved to the helmet. The pilot's head, in effect, becomes a very sophisticated and ergonomically attractive direction controller, thereby integrating the pilot's visual/monitor skills with the specialized accuracies of weapon and navigation systems.

The Helmet Mounted Display (HMD) as opposed to just a sight, combines a Helmet Angle and Position Sensing System with a helmet mounted high resolution display and optics to provide a highly flexible system incorporating many of the facilities to be found in both head-up and head-down displays. Because it is a quality imaging system, it is possible to present both pictorial and symbolic information together offering a combination of synthetic imaging and sighting information.

The recent developments concerned with miniature cathode-ray tubes has ensured that in spite of their size (19 mm dia.) there is no reduction in performance from these devices. Also by mounting a miniature CRT on the helmet close to the eye this effectively provides the equivalent of a much larger panel-mounted CRT with the advantage in saving both weight and power in the process.

Under good viewing conditions the eye can resolve 0.25 milliradian and it is quite obvious that the performance from the display will fall short of this. It is, however, very important to get the maximum benefit from the HMD by having high resolution for the picture.

Another very important factor associated with Helmet Mounted Displays is that the picture scale and viewing angle should not be compromised by limitations in the optics. The first factor to be realized is that the image to be displayed will be collimated to appear at infinity since it should register with the outside world. Secondly, the instantaneous viewing angle should preferably be 40 degrees in azimuth and 30 degrees in elevation with an exit pupil of 2.5 cm to accommodate a range of users.

When one bears in mind that the objective of such a design must be to achieve the above specification with the least weight penalty and with minimal obstruction to direct vision, some idea of the problem emerges. The best solution appears to lie in the use of a diffractive optical element preferably embodied in the visor which will both focus the image at infinity and operate as a high efficiency (90%) reflector at the narrow band wavelength of the CRT phosphor but offering see-through ability at all other visible wavelengths. Color switching is a possible option. It is appropriate to discuss mechanical aspects here before leaving the optics. The first concerns the weight of the CRT package and optics on one side of the helmet. This should be counterbalanced by a similar weight on the opposite side. The second is adjustment of the optics to compensate for different users. Such an adjustment to ensure that the center-line of the optics is aligned with the user's eye-ball may reduce the exit pupil size with corresponding reduc-

tion in the size of the diffractive optic. Also an interesting solution might be to mount the CRT off the helmet and transfer the image via a fiber-optics pipe to the helmet. This also removes high voltage from the helmet. At present, however, suitable light pipes degrade the picture and at the same time impose undue constraints on the helmet.

There could be considerable advantages in providing images to both eyes. This would combat the inevitable binocular rivalry which will otherwise occur and would ensure harmonized viewing by both eyes. However high vibration can cause convergence problems and flicker detection may be increased with biocular viewing (Ref. 12).

The principal advantage of the Helmet Mounted Display lies in the fact that data is presented to the eye irrespective of the direction of regard. This is particularly important when operating at high speed close to the ground. The data can be conveyed subjectively to the eye while the pilot's concentration is focused on flying. Also in the surveillance operational role both during the day in poor visibility, and at night, the ability to slew sensors directly so that the sensor is oriented to the viewing direction of the pilot, provides a "head out of the cockpit" capability.

MISSION MANAGEMENT DISPLAYS (MMD)

The first three display applications (HUD, HDD, HMD) are used to display information used by the pilot for primary flight control. The displays appear centrally located relative to the pilot's visual scan so as to attract his primary attention. Mission management displays are more likely to be positioned to one side than to be centrally located with respect to the pilot (see Fig. 5). They include map displays, aircraft situation data, and aircraft subsystems data such as engine, fuel, hydraulic, oxygen, ordnance, navigation, communications, countermeasures, etc. One example is a flexible information format to display computer generated vector graphic aircraft situation data. Another example is an optically combined display of tactical data overlaid on the microfilm image of an aeronautical chart.

The first example is a graphic display that has no requirements for video presentations. A two- to three-shade of grey display can take advantage of sizes from 10 cm x 10 cm for the display of the more conventional flight control data up to 30 cm x 30 cm for the display of terrain contours, contact analog situation data, symbolic map data such as threats, weapon engagement perimeters, computer synthesized targets, computed optimal flight paths, and navigation displays. For a scanned matrix display a minimum resolution of 2.5 pixels/mm and up to 250 Hz refresh rate for the display of vector-graphic display imagery is necessary. The requirement is based on the minimum requirements to provide both the appearance of smooth continuous image motion and simultaneously the precise scales, pointer positioning, vector rotation, and vector translation positioning accuracies needed for the rapid, accurate presentation of vertical and horizontal scale, bar-graph, round dial, graphical, symbolic map, and perspective information formats. This

pixel density also allows the presentation of upright numerics and alphanumerics in highly legible and identifiably 10 x 14 dual stroke width or larger fonts. Small, visually complex characters, i.e., alphanumerics, to be rotated, must have stroke widths that contain a minimum of three pixels and simultaneously satisfy the 15 per cent of character height requirement of good legibility (e.g., 15 x 21 array font size or greater independent of display element density).

Presently being used are monochrome CRTs utilizing two discrete luminance levels in addition to off. Current sizes are approximately 12 cm x 18 cm, oriented as a normal page of a book. This size is a compromise between that requested by human factors studies and limitations based on airframe installation requirements. Present studies of systems utilizing CRTs indicate that an alphanumeric character must be at least 5.5 mm high, with an ideal height being 6.5 mm (assuming a 70 cm viewing distance). The graphics capability should include simple graphs, geometric shapes and lines generated by a display with uniformly spaced horizontal and vertical picture elements. Color is desirable to accentuate information.

Certain applications may favor the display of actual aeronautical charts which have resulted from a long interplay between cartographers and users (3). Although they are not always ideal for display purposes, charts from this mainstream of development are likely to form the basis of future displays. Their optimum display demands high resolution, full color for the projected map although the overwritten data can be monochrome.

An optically combined display provides high resolution color as well as being compatible with a full electronic display suite. It provides a form of dual redundancy and installs in a single unit. An alternative using the same data base is the remotely scanned map, which depends on the availability of a full color high resolution display embodying a proper solution to the problems of high ambient light.

The all digital solution is a possibility which awaits a viable solution of the editorial and logistic problems of a digital data base together with a proper full color display head. There are considerable digital hardware and software problems and the storage required could be massive, even in terms of devices such as bubble memories. Bearing in mind the complexity of cartography as an activity and the long history which has led to present mapping material, it would be a considerable task to demonstrate that such a system is operationally superior to a combined display. It is possible to filter information with an all digital data base, e.g., show SAM sites or all radar on demand.

KEYBOARD DISPLAYS

Keyboard displays afford the possibility of combining separate symbols into one functional command, thereby integrating the control of several sets of functions presently provided by separate dedicated control panels and the management of several primary multifunction displays. They can reduce operator real-time workload both by allowing preselection of flight tasks on a functional or mission segment basis and by providing flexible but

orderly procedures in the conduct of the total crew station management. Through the incorporation of programmable switches and information processing, the plethora of dedicated control switches can be sharply reduced.

It is typical to have a legend area for each switch which consists of two rows of four to eight characters per row. The individual legend should use as a minimum a five by seven matrix, although a seven by nine matrix is preferred. Examples of each font are shown in Fig. 8 and Fig. 9. Experiments have established (9), (10), (11) that a 5 x 7 matrix is the minimum required while matrices larger than 7 x 9 do not lead to meaningful improvements. Character generators using 5 x 7 and 7 x 9 are the ones most readily available. Fifteen to thirty switches are desirable. The legends should be viewable under bright sunlight at a minimum contrast ratio of 1.2 and for some applications be usable with night vision goggles.

ALPHANUMERIC MODULES

Modular readout devices, specifically alphanumerics and bargraphs, are needed to provide legible, reliable, variable-format control display components. Readouts will be needed both in discrete and mosaic formats to allow variable fonts and positioning in alphanumeric modes and/or line positioning for bargraph applications. Discrete readouts take the form of individual or grouped alphanumerics. They are used in applications which range from one or two digit displays and legend lamps, to message displays of several rows of up to 20 or more characters per row. Reference 13 discusses these applications in more detail.

These devices can be developed as modules employing three basic forms:

- o Segmented numerics
- o Dot-matrix alphanumerics
- o Small area mosaics

It is desirable that these modules should be constructed so they can be abutted on all four sides and incorporate all necessary drive and address circuitry. This concept will allow a wide variety of form factors and display areas which are appropriate for application of these devices. Applications include: control panel numeric and alphanumeric readouts; flight, mode, and caution legend lamps; and multi-legend display switches. The devices need to be readable in bright sunlight as well as with night-vision goggles. The resolution should be from one to six pixels per millimeter.

SUMMARY

The environment where the visual communications link between aircraft systems and their human operators takes place has been described. An historical perspective showed a revolutionary trend away from a proliferation of electromechanical dials to a smaller number of electronic displays. The applications for electronic display technology were divided into four classifications of visual format based primarily on the maximum number of pixels required. Six specific applications were described and each was considered to

span two of the visualization formats.

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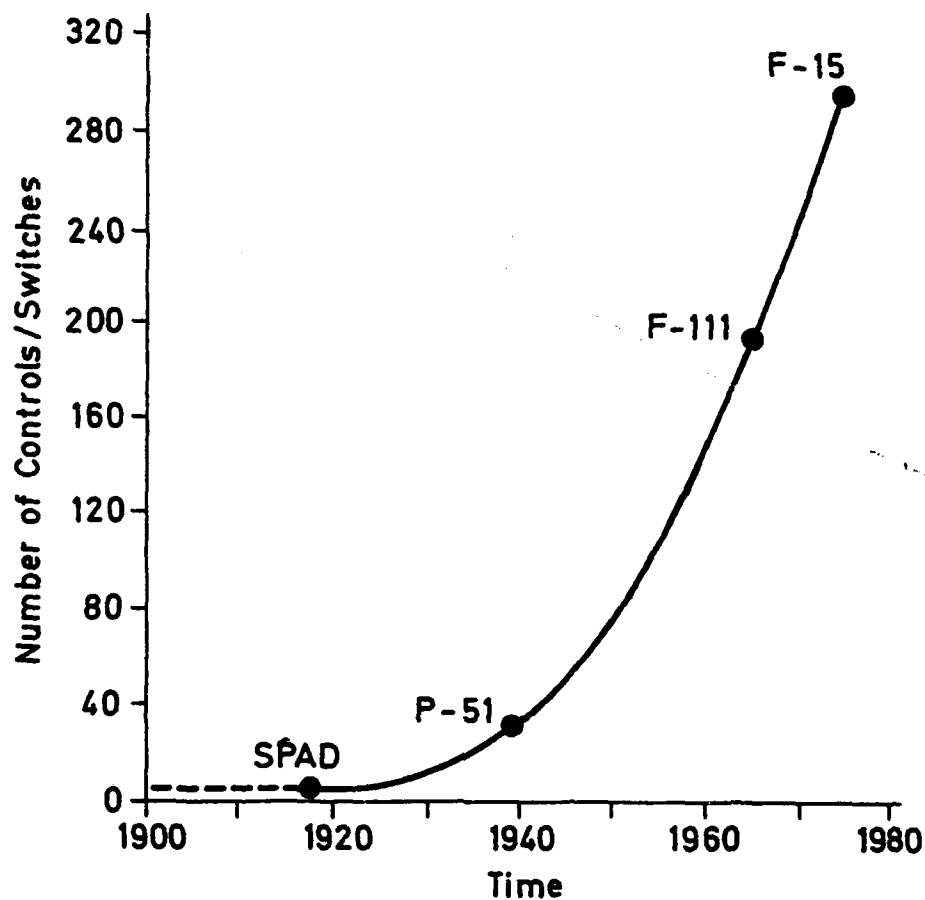


Fig.1 Growth of number of switches per crew member for 4 aircraft (Ref.14)

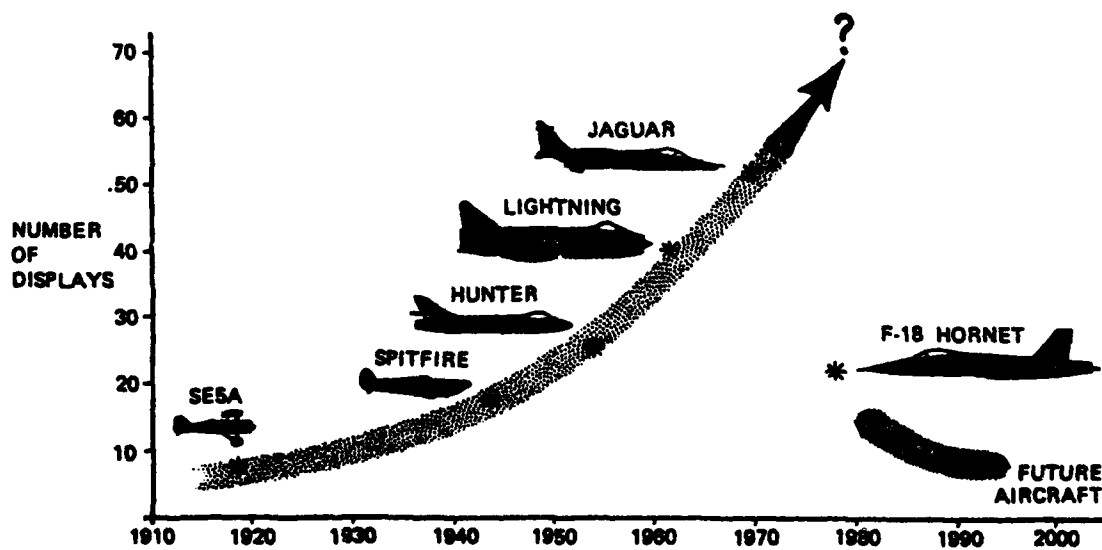


Fig.2 Growth of cockpit displays (Ref.15)

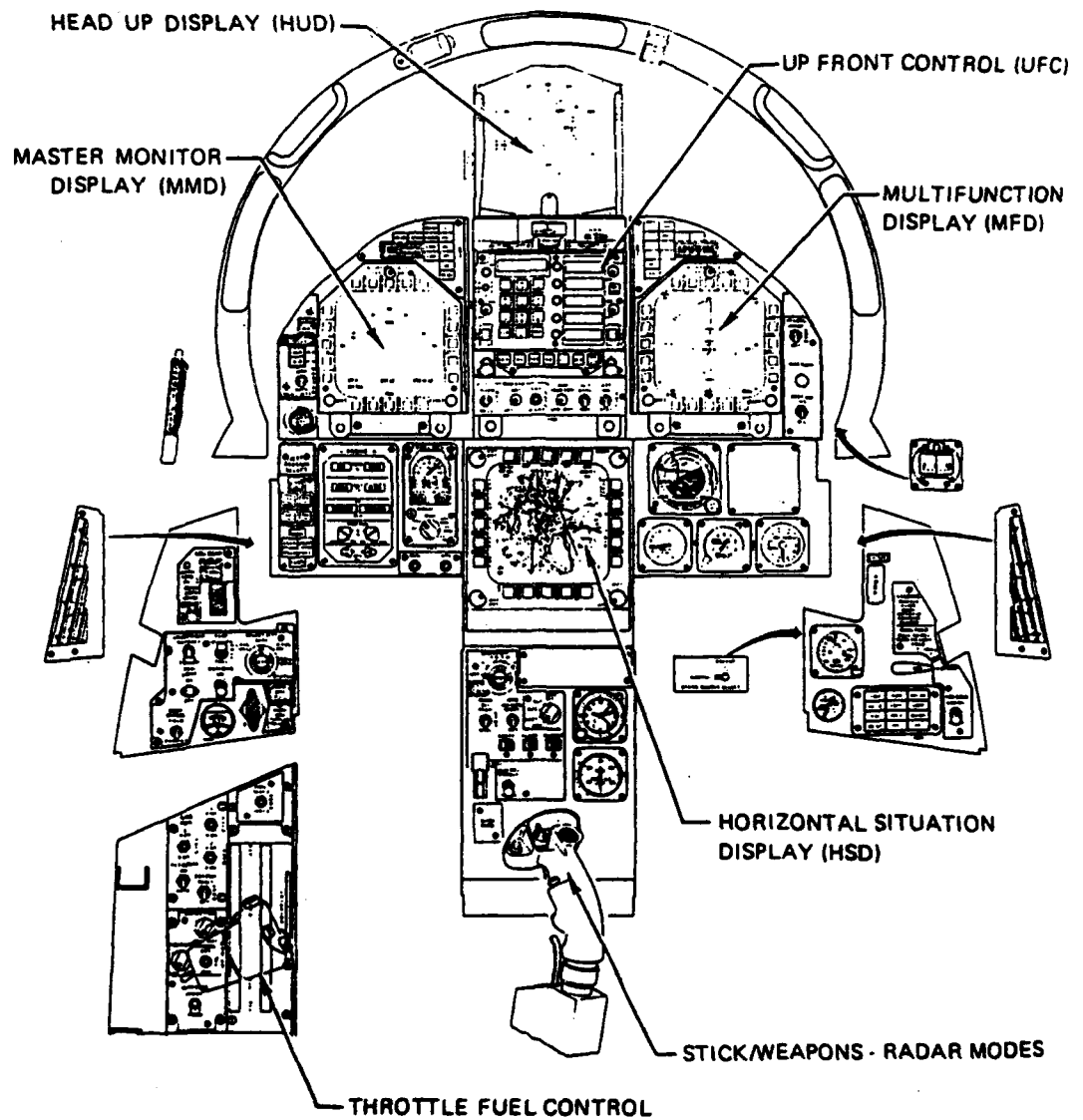


Fig.3 F/A-18 Crew station (Ref.16)

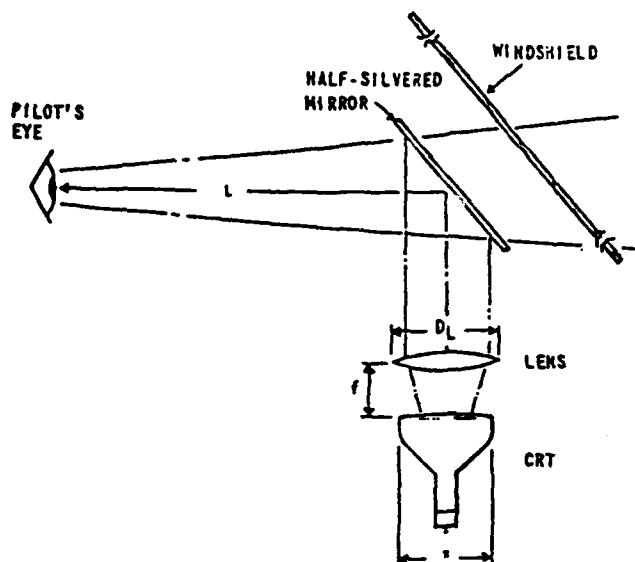


Fig.4 Head up display (HUD) optics

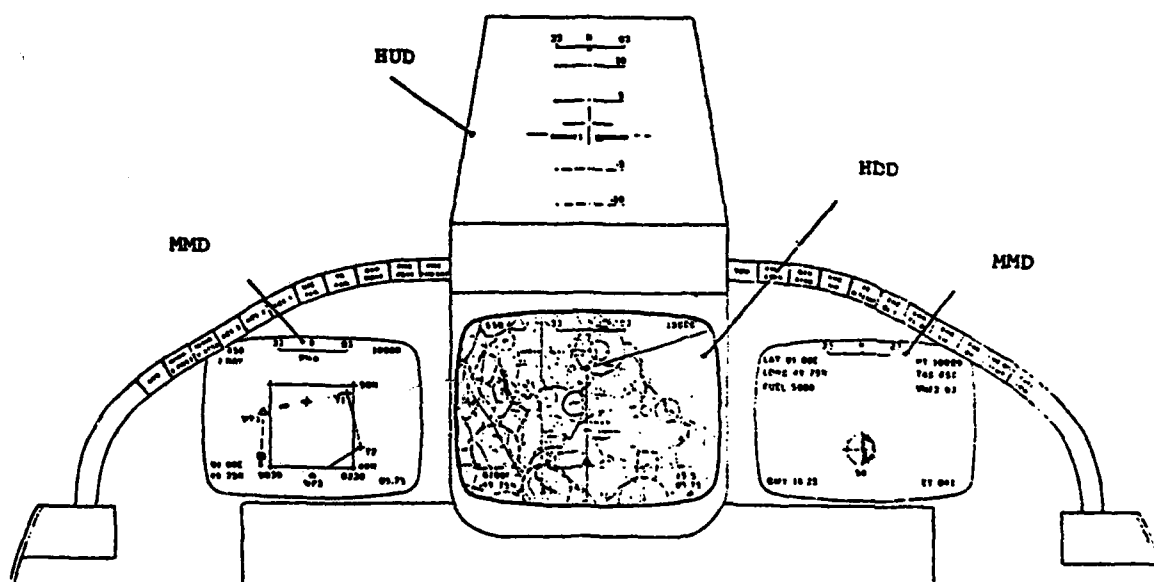


Fig.5 Cockpit orientation of displays

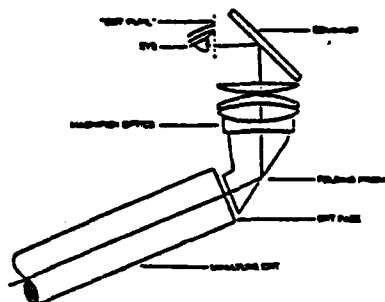


Fig.6 Simple magnifier HMD with flat combiner;
Hughes Aircraft Co. Reference 6

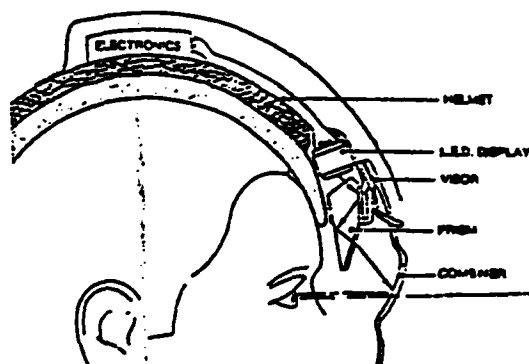


Fig.7 Simple magnifier HMD using LED image source
and spherical combiner; Marconi Aviation, Reference 7

A B C D E F
G H I J K L
M N O P Q R
S T U V W X
Y Z 0 1 2 3
4 5 6 7 8 9

Fig.8 Modified Huddleston Font 5 x 7 Dot Matrix.
Reference 8

A B C D E F
G H I J K L
M N O P Q R
S T U V W X
Y Z 1 2 3 4
5 6 7 8 9 -
? & / + , =

Fig.9 Sherr 7 x 9 Dot Matrix Font. Reference 9

CATHODE RAY TUBES

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1 HISTORICAL SURVEY

The cathode ray tube (CRT) is one of the earliest electro-optical devices, and its name derives from experiments on the effect of degree of vacuum on electric discharge in a gas. At a low pressure (10^{-2} mm Hg) a greenish glow was produced on the glass surface of the tube when a high potential caused electrons to be stripped from the cathode and to strike the glass.

The study of that fluorescence of glass was commenced by Plücker in 1859 ; Goldstein in 1876 thought it was produced by "ether radiation" and gave it the name of "Cathode Rays". Crookes (in 1879-1885) suggested that the rays were made of electrified particles reaching high velocities by virtue of the electrical forces near the cathode surface. Perrin in 1895 showed that the charge was negative, and J.J. Thomson in 1897-98 measured its mass (1/1840 th of that of Hydrogen atom) and its charge (that of Hydrogen ion). In 1911 Rutherford established his theory of nuclear atom, whereby atoms are made of particles of equal and opposite charges : protons and electrons.

Finally it turned-out that Plucker's cathode ray was nothing else than a stream of "electrons" (as we say today after the name previously suggested by Johnstone Stoney).

Although 'electron beam tube' would therefore be a much more accurate description, the earlier name is so well established that it is unlikely ever to be displaced and it is so widely spread that the acronym CRT is often employed in the informatic broken English to designate any whole display terminal.

The phenomenon that cathode rays (electron beams) are deflected by electric and magnetic fields led to the use of the tube as a laboratory measuring device. The successive developments to transform this simple device into a practical display include among others the incorporation of a flat phosphor display screen (Braun 1897 who produced the first cathode ray tube where electrons were deflected by internal plates), the use of a heated cathode (Barium oxide coated; Wehnelt 1904 who also introduced a control electrode which retains his name) and the use of aluminum backing of the phosphor screen. By 1908 Campbell Swinton was suggesting the use of the CRT for transmitting and reproducing television images, and during the 1920s and 1930s the CRT was used in much of the radio and electronic research then under way.

Use of the CRT in aircraft dates back to the late 1930s, when airborne radar and electronic navigation systems incorporated CRTs as displays for the equipment operators (1). These tubes were always cursively-written, a technique similar to laboratory oscilloscope writing, and quite distinct from TV raster type of presentation which has only come into use in aircraft quite recently. Development of CRTs since that time has steadily progressed so that a wide range of monochrome tubes is now available for use in many different applications (2).

Multicolor CRTs are a much more recent development. The first scheme to be taken to the stage of large-scale production was the RCA "shadowmask" on which development was started in 1949 and which went into production in 1954, although during the period 1954 to 1968 there were still many important advances made in manufacturing technology and tube characteristics. Since 1968 further improvements include the introduction of the Trinitron and the black-matrix phosphor screen, as well as the appearance of the penetration tube as a viable color tube contender albeit with a more limited color range. The use of color CRTs for the display of information in aircraft cockpits is still recent, but it appears likely that most civil aircraft will use them extensively in the near future, followed by military aircraft applications (3).

2 PRINCIPLES OF OPERATIONS

2.1 Monochrome tubes

The basic principle of the CRT in its most simple form is shown in Fig. 1. The main structure consists of an evacuated envelope in the form of a glass or metal bottle with a narrow neck flaring towards the front display surface, rectangular or circular. Within the neck is an electron gun which projects a beam of electrons towards the phosphor screen deposited on the front surface, the electrons being accelerated by the large potential difference (typically in the range 10 kV to 30 kV) established between the gun and the anodes and screen. The beam is deflected so that it can strike any part of the screen, and is modulated in intensity so as to vary the perceived luminance of the screen.

From there on, an extraordinary number of variants may be designed since the basic CRT can be divided into four electro-optic regions, plus the screen itself:

- the electron-beam formation region
- the beam focusing region
- the deflection region
- the drift region

+ Beam formation

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a. A cathode emits electrons which are extracted, concentrated and controlled by sets of electrodes.

- The luminance of the output screen results from the energy density in the beam. At a given accelerating voltage of the electrons, this is related only with the electrons density.
- The resolution is also obviously related with the size of the beam.
- It has been demonstrated (Hamilton - 1830) that there is a mathematical analogy between the laws concerning light rays and charged particles (electron optics and electromagnetic lenses).

As a result, the size of the image (focused spot on the screen) is proportional to the size of the object (the cathode), to the screen to lens distance $\underline{l'}$ and inversely proportional to the cathode to lens distance \underline{l} and to the square root of acceleration voltage U (fig 2).

In many instances, in a CRT $\underline{l'}$ is much longer than \underline{l} , which would lead to a large magnification and an increase in U is paid by a loss of deflection sensitivity as will be seen later.

Therefore to get a small spot a very small cathode area is necessary.

- Moreover :

- . Lens aberrations tend to enlarge spot size
- . Two other phenomena of fundamental nature also contribute to limit the resolution :
- . space charge (charged particles repel each other in the drift region which therefore enlarges the beam).
- . current density is limited by the velocity distribution in the electron beam and is inversely related with magnification squared.

For all these reasons, it is mandatory to have the highest possible current density at the cathode.

The current delivered by a cathode is a function of its temperature and of the cathode to anode potential difference :

- . At constant temperature, the saturation current is : $i = kV^{3/2}$
- . As a function of temperature, the saturated cathode current is described by the Richardson-Dushman law (Table 1 which gives characteristic values for pure metals and alkaline earths).

Thoriated Tungsten cathodes are universally used in high power grid tubes but operate at fairly high temperatures.

Oxide cathodes which were until very recently also universally used in cathode ray tubes consist of a thin layer of barium-strontium oxides mixture, some hundredths of a millimeter thick, deposited on the top of a nickel cylinder internally heated by a small filament in close contact. The merit of these oxides is to considerably lower the work function and "b" of the surface so as to increase the electron emission and reduce the working temperature.

It is not possible however to reach very high current densities without a very significant reduction in life. One of the reasons for this is the resistance of the oxide itself and at the interface with the metal, which lead to a cumulative overheating process.

In practice the temperature must be kept between fairly tight limits (1000 to 1130 K). Under that the cathode is poisoned in several hundred hours, and above there is a sublimation of cathode active materials with corresponding exhaustion and parasitic emission of other electrodes on which these materials condense. Therefore although the possible values of current density vary from 0.1 A.cm^{-2} at 700 K to 100 A.cm^{-2} at 1200 K, in practice 0.3 A.cm^{-2} is considered an optimum value in a CRT, leading to an average cathode life of 10 000 hours.

This by far exceeds the actual need for use in a military aircraft, and it is possible to operate cockpit CRTs for, say, 1000 hours at around 1 A.cm^{-2} .

In dispenser cathodes, instead of being deposited on a sheet of nickel, the active material - basically barium - is impregnated in the cavities of a "sponge" of tungsten, sometimes covered by a layer of osmium (4) (5).

As compared with the oxide coated cathodes, the dispenser (or impregnated) cathode may be operated at a slightly higher temperature (+ 100°C) with useful current densities of more than 1 A.cm^{-2} and life in excess of 50 000 hours.

Still higher current densities could be bartered with reduced lives (not a problem as said) and higher temperatures. The difficulty remains barium sublimation and condensation on colder electrodes.

Besides, they require a better vacuum to avoid poisoning and this leads to a longer and somewhat more expensive processing.

The type of scanning and of image to be displayed also influence the cathode load.

In regular TV raster, the scanning is fast and the required peak luminance to obtain the brightest areas lead to high peak currents. If only alphanumerics are to be presented in TV raster the average current will be much lower than in TV picture.

Now the same alphanumerics are displayed in stroke writing ; the average current will be very close to the peak current and as the "image" content is limited, the writing speed may be low for a similar trace luminance.

In dual mode operation - for instance in "Head Down Displays" - the writing speed is imposed by the TV standard. It defines the "flyback" time (some % of total frame duration) during which vectors and characters are stroke written. To be legible on the "image" background, they must be somewhat brighter. As brightness and writing speed must be high, it results that beam current must be very high. This latter mode of operation is probably the most exacting for cathode load even when compared with HUD because in the latter in spite of the very high luminance required, the writing speed may be very low thanks to the small amount of information.

b. The remaining beam forming electrodes may basically be organised in a triode or tetrode structure with a Wehnelt (g1) control electrode. (Fig.3)

- The former (triode) where the accelerating electrode (g_2) is often tied with the screen requires one power supply less than the latter. However, in order to avoid the need for a very high (negative) voltage to control the beam, g_1 must be distant from that electrode. This may result in a degradation of the resolution due to space charge effects in the g_1 - g_2 region.

- The latter uses a second electrode operated at a fixed low voltage (≈ 1000 V), thus minimizing the Wehnelt voltage swing necessary for control. Moreover it makes it independent of focus and screen voltages and allows a shorter $g_1 - g_2$ spacing with resulting reduction of space charge repulsion effect.

- These arrangements of electrodes and voltages are generally such that a strong curvature of equipotential surfaces occur in the vicinity of the cathode. This compels the electrons to all converge within a short distance from the cathode at the so called "cross-over" point. The electric field is higher at the center than at the edges of the cathode and so is the emission density. It is this cross-over point which is imaged onto the screen.

Alternatively, by properly shaping the electrodes it is possible to have a uniform field applied to the cathode, and hence a more uniform emission density and "laminar flow" electron beam. Additionally this avoids the "crossing over" of the electrons with its corresponding high space charge repulsion, but on the other hand prevents apparent electron source size reduction.

+ Beam focusing

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Beam focusing may be electromagnetic or electrostatic

a) Magnetic focusing (Fig.4)

In a uniform field H parallel to the axis, electrons with a lateral velocity component will experience a constant radial acceleration and describe a circle while they travel axially and the trajectories are helices of pitch L . After a time t depending only of the magnetic field, all electrons starting from the same object point will reach the same image point at a distance L ; the whole cathode or cross over point surface produces an image of the same size. In practice, a short coil is used, and electric fields are applied. The helices described by the electrons in a uniform magnetic field become spirals on a kind of cone.

The equation which relates the different parameters and the focus current shows that

- . the required focusing current is proportional to only the square root of the accelerating voltage, which is interesting for high brightness (high voltage) tubes. . the shorter the focal (and tube) length, the higher the current (and power consumption)
- . d , neck diameter has to be minimized
- . l' , coil to screen distance has to be minimised

Electromagnetic Focusing provides the highest resolution

b) Electrostatic focusing (Fig.5)

Set of electrodes where appropriate voltages are applied shape equipotential surfaces so that electrons are forced to converge.

Two main types of lenses are used :

The high voltage or bipotential gun.

This structure is basically composed of two elements, operated at different potentials. The first one is the region between the g^2 electrode of the beam forming structure and the focus electrode g_3 held at around 20 % of screen voltage (hence the name). The second one is the region between the focus and another electrode g_4 set at screen voltage.

The resolution is somewhat lower than with EM focusing but larger than with "low voltage focus". It is closely related with focus voltage adjustment. Here spot size is also directly related with focus electrode aperture size. Depending on it, the electrode may capture some beam current with resulting power consumption.

The low voltage or unipotential or "einzel lens" gun. (in german einzeln = single). Here the focus voltage is lower (0-500 volts) than on the two adjacent electrodes, held on both sides at the same higher potential.

The resolution is still lower due to strong aberrations of this type of lens. However it does not depend upon focus voltage, and focus electrode does not draw any current. By the use of a narrower aperture, resolution may be increased but then grid current takes place.

In some instances an auxiliary "dynamic focusing" is used in order to compensate for the defocusing resulting from the variation of the length of the trajectories between the center and the edges of the screen. A voltage, variable in accordance with the spot distance is applied to an auxiliary electrode. A better and more uniform resolution is thus obtained.

+ Deflection

Either of two types can be used to deflect the electron beam.

Deflection may be periodic in raster scan along x and y axis, or in polar coordinates (PPI : Plane Position Indicator) or "random", rather called vector or stroke writing (sometimes calligraphic; and in french "balayage cavalier" : Knight movement).

Whatever the type of scanning, the addressed points can be described by their x and y coordinates which means that deflection fields are to be produced along two directions. For simplicity one single method is used for both : electromagnetic or electrostatic.

a) Electromagnetic deflection

The same basic equations as for focalisation apply (Fig.6).

Only the square root of accelerating voltage commands the amplitude and the deflection current for a given amplitude, allowing high voltages, hence high luminance. Changing the value of the current in an inductance requires high energy. This precludes the use of EM deflection in high speed tubes (except if a quasi resonant circuit can be used like in raster scan). Therefore also, in stroke writing high power amplifiers are necessary to settle and move the spot rapidly.

b) Electrostatic deflection

Here the deflection amplitude is linearly dependent on the screen voltage (Fig.7).

To deflect the beam it is only necessary to charge the capacitor represented by the plates, which requires little energy. However it increases with the deflection speed where, in turn, a high deflection sensitivity is needed to avoid use of expensive driving components. A moderate screen voltage would become necessary but the luminance and resolution would be low.

A solution consisting of a Post Deflection Acceleration structure (PDA) prevents this screen voltage limitation. It may be (Fig.8) :

- a resistive spiral between screen and deflection region whereby electrons are progressively accelerated. The "compression ratio" varies from 0,6 to 0,8 depending upon ultor voltage.
- a field mesh, crossed by the electrons and set at a potential close to that of deflection plates. It can be flat, further improving the anti compression effect, or "domed".

In that instance it can be designed so that electrons entering the drift region cross orthogonally the equipotential surfaces after the mesh. The deflection sensitivity is then totally unrelated with screen voltage. It can even be profiled so as to amplify the deflection.

This last solution is very useful for large size, high speed, high luminance electrostatic CRTs. The drawback is a dull halo surrounding the spot which is due to electrons scattered by the mesh which also captures a little amount of beam current.

The other two have been widely used in oscilloscope CRTs.

+ Screen

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At present screens are made of one or several layers of powdered (see below) material deposited on the face plate of the CRT. The process by which, when hit by high energy electrons such a material emits light is called "cathodo-luminescence" and the material is normally described as a "phosphor".

The whole screen is set at a high potential (with respect to the cathode) by which the electrons of the beam are accelerated. Such a bombardment of the material results in some secondary emission which, under certain circumstances would build up negative charges on the screen and in turn restrain the electrons from reaching it. A thin aluminum backing of the screen prevents this, maintains the screen unipotential, and moreover increases the light output by reflecting to the front the light emitted to the back. Besides, it also protects the screen phosphor against ion bombardment and resulting localized ageing. The layer thickness is such that only a few (2-4) kV are lost by electrons for crossing it but this precludes however its applicability to tubes that operate at low voltages (up to 5 kV). Many crystalline materials have been used as phosphors in which controlled amounts of impurities (activators) provide selected colors. More recently the "rare-earths" phosphors have been developed, initially in view of color television. In these materials the electrons excited by the high energy beam, drop from one energy band to another, the freed energy being converted into photons.

a. Temporal characteristics : (Fig.9)

Under an excitation of sufficient duration the luminance first increases during the "rise time" t_m and stabilizes at a maximum value L_c ; this is the "fluorescence". After removal of excitation, the luminance does not disappear suddenly and decays according to hyperbolic or exponential laws; physically this is the "phosphorescence"; technically this is the "persistence".

Rise time is generally shorter than "decay time" τ_d for which several values (at 1/e, 10 % and 1 % of L_c) can be quoted. They may differ by a factor of 10 or more for long persistence materials. Typical values range from 10 or 50 nano sec to 1 or several seconds. The comparison of τ_d at 10 % and at 1 % gives a good indication of the steepness of the decay curve. The values of t_m at 90 % of L_c and at 10 % are generally of the same order of magnitude.

When the excitation period is short, it may happen that no steady state in luminance is reached. The two values of persistence are then much shorter than when the phosphor is saturated.

When the excitation is short but repeated at a sufficient frequency a cumulative process: the luminance build-up, takes place. When the stable state is reached the luminance is represented by a sawtooth curve, the fluctuation resulting for the eye is the "flicker" effect.

b. Spectral characteristics : (Fig.10)

Phosphors with luminescence and phosphorescence in the visible spectrum can be conveniently described by their trichromatic coordinates in the CIE chromaticity diagram (or their equivalent wavelength and saturation). This can be completed by the spectral

emission curves. Phosphors for all colors plus U.V and I.R. are available and for reproduction of most colors by additive synthesis in the eye.

c. Conversion efficiency :

The conversion efficiency of cathodoluminescence ($10-50 \text{ lm.W}^{-1}$) exceeds by one to several orders of magnitude that of all other electrooptical effects (Table II). It can be expressed in several ways (Fig. 11a) :

- . Energy efficiency : watts of radiant energy per watt of excitation power.
- . Luminous efficiency : radiant lumens per watt of excitation (visible light only).
- . Luminous equivalent energy : radiant lumens per watt of radiant energy (depends upon spectral emission characteristic of the phosphor)

d. Life : (Fig. 11b)

Crystal lattice is slowly modified by electrons bombardment. The major factor is the total number of charges received along the time per unit area of screen: Coulombs per cm^2 . It has a stronger action on efficiency than on decay time d. For most practical current levels, phosphors are available with lives of several thousand hours.

e. Phosphor types :

The characteristics of more than 50 types are listed in the JEDEC P number register operated by the US Electronic Industries Association, who have also issued guidelines on phosphor measurement methods. This large variety is necessary to fulfill the different needs. Some phosphors (Fig. 12) are made of a single material ; some others (P4, P17, P29, P40, P41) are made of a blend of materials. They may provide a single color or different colors for fluorescence and phosphorescence, depending upon the rise and decay characteristics of the materials. In others (P7, P14) a UV component in the fluorescence spectrum of the first material produces by photoluminescence a long lasting phosphorescence in the second (cascade phosphors). A description of recent development in CRT phosphors has been given by Woodcock and Leyland (6).

It must be emphasized that the characteristics a. through e. mentioned above do strongly depend upon chemical composition (purity, activators), particle size, deposition method, tube processing, operating conditions (current density, high voltage). Therefore considerable differences may be observed in practice, and different alleged proprietary performances may just depend of particular choices of conditions.

2.2 Color tubes

The "simple" CRT described above produces a monochrome picture, the color of which is determined by the phosphor characteristics. The generation of a multicolor picture is a more difficult task and requires a significant complication of the basic tube technique. Several alternative methods of producing color pictures have been devised.

+ Shadowmask color tubes

The shadow-mask CRT has been designed to deliver a TV image exhibiting all the visible colors. The basic arrangement of this is shown in Fig. 13. As compared with the monochrome tube, the principal changes are the provision of three guns, the addition of the shadowmask, and the patterning of the phosphor screen. The phosphor screen is printed in the form of an array of 'triads', each triad consisting of a dot of each of the primary phosphor colors, red, green and blue. The geometry of the guns, shadowmask and screen is arranged so that the beam from each gun can fall on only one colored dot in each triad. Thus the three guns can be independently fed with the required modulation signals of the three primary colors. The three beams pass through the same magnetic deflection coils with the same electron velocities and are therefore deflected together, by approximately

the same amount, and the electrostatic focus elements are generally also common so that a single focus control is sufficient.

This arrangement requires very exact alignment of the guns, mask and phosphor pattern, which is obtained with good yield thanks to techniques now well established. The most recent developments in shadowmask CRTs for the domestic market have concentrated principally upon improving the contrast through the use of a black matrix screen to fill in the areas between the phosphor dots, the reduction in length of tube by increasing beam deflection angles and the introduction of in-line guns. An arrangement also used in conjunction with striped phosphor patterns and slotted shadowmasks such as in the 'Trinitron' CRT.

In the context of airborne applications, the principle difficulties arise due to lack of luminance and to environmental limitations. Considerable loss of electron-beam current occurs at the shadowmask, so that typically only 15-30% of the average beam current reaches the phosphor. Apart from the loss of luminance this also creates the problem in high brightness tubes that the energy absorbed in the shadowmask can cause thermal expansion and thereby upset the exact alignment between shadowmask and phosphor screen. The second luminance problem arises because the luminous efficiency of red and blue phosphors is significantly less than for high efficiency green phosphors. A third difficulty is that whereas with monochrome tubes low luminance can to some extent be compensated by using narrow-band colored filters in front of the tube to minimise reflection, with shadowmask and other color tubes it is not easy to produce filters to match all three phosphor colors. For these reasons, airborne shadowmask tubes have not yet fully matched the high luminance requirements of military users although they are now finding increasing use in civil aircraft.

Application in the aircraft cockpit environment also creates vibration problems. The shadowmask is necessarily a thin and rather flimsy structure, which can be excited into resonances by external vibration, with consequent effect upon alignment and therefore upon the tube's color purity. These problems have been substantially solved for the civil aircraft vibration levels, and recent developments suggest that rugged tubes suitable for military aircraft environments may soon be available.

+ Beam index color tubes

An alternative to the shadowmask tube which is similar in some respects but avoids the structural problems of the shadowmask is the beam-index tube (7), (8). (Fig.14). The phosphor screen is arranged in a pattern of stripes similar to those of the 'Trinitron' CRT, but instead of using a mechanical mask to ensure that only the correct phosphor is energised by the beam, it uses electronic control. A single gun is used and the beam is scanned across the stripes in a raster mode (cursive writing is not generally possible), the beam current being modulated so that the appropriate levels of current are used to excite each of the three colors in turn. To achieve good color purity the beam width must be very narrow, and the beam modulation must be exactly synchronised to the beam position. This synchronisation is achieved by putting onto the rear of the phosphor a fourth series of stripes in the form of a UV or X-ray emitting phosphor. In each case the emission is detected and its timing is used to synchronise the beam current modulator to the scan deflection waveform, through the fast acting control loop. An alternative method of obtaining the synchronisation signal has been described by Turner (9) ; this uses a pattern on the aluminum film behind the phosphor screen to generate a signal in the return beam-current from the film.

This CRT design is mechanically much simpler and rugged than the shadowmask. One of the major likely reasons for its oblivion for 20 years has been the difficulty of making in an economical way such a broad-band control loop with the required phase stability.

Now that cheap high speed solid state components flourish it is gaining renewed interest for instance for small size true 625 lines resolution tubes well suited for cockpit environment. The second major difficulty is to obtain a sharp edged spot of constant size under various beam current conditions and to switch it fast enough to maintain color purity at all luminance levels.(10)

Luminance is not very much better than in a shadow mask CRT because even if the mask electrons transmission is only 20-30 % , these energize each color dot for the whole "dot" time whereas the single beam in the index tube devotes less than 30 % of the time to each color stripe.

Besides in order to detect its position it is not possible to cut completely off the beam, thus reducing the contrast. It is quite likely though that most of these difficulties could be easily overcome provided appropriate development efforts are made.

+ Penetration phosphor tube

The third technique for color CRTs is the Beam Penetration or 'Penetron' tubes, which is also of much simpler construction than the shadowmask type and is similar to that of the monochrome tube, except that colors are obtained by the particular characteristics of the phosphor screen (10) (Fig.15a).

The screen is formed of a combination of two types of phosphor material, which are generally chosen to emit green light and red light. In one arrangement so called "onion skin" the green phosphor particules are coated with a layer of red phosphor. It is also arranged that the EHT potential applied to the screen can be set at any value between typically 17 kV and 10 kV. At the lower limit the electrons are unable to penetrate the barrier layer surrounding the green phosphor particles, and only red light is emitted from the screen due to electron excitation of the red phosphor material (Fig.15b). At the higher limit the electrons penetrate the barrier and excite the green phosphor particles, so that both green and red emissions are produced. Because the efficiency of the green phosphor material is generally greater than that of the red, the resultant color is a reasonably pure green.

For intermediate EHT values, a range of different colors is obtained resulting from the addition of red and green in different proportions. However the use of only these two primary colors necessarily restricts the range of colors which may be generated, to a single line on the color triangle, and in fact it is generally possible to produce only four distinct colors (red, orange, yellow and green), and in high ambient illumination possibly only three. Other spectral or temporal characteristics are also possible by choosing phosphors with different color/storage/decay properties.

The principal advantages of this type of tube are the rugged mechanical construction and the high resolution. Therefore it can be used in any vibration environment for which a monochrome tube is suitable, i.e. any reasonable cockpit environment. Also, the absence of any pattern on the phosphor screen means that tube resolution is limited by beam width rather than by the size of the phosphor dots or lines, so that high resolution is possible. Patterned contrasted filters can also be used without forming moiré fringing effects.

Although the luminance is not reduced by the same mechanisms as in the shadowmask tube, it is still significantly below that of the monochrome CRT (Fig.16). This is principally for the red color, and is due in part to the relative inefficiencies of red phosphors and also due to the low excitation voltage. Moreover the green color is also generated inefficiently, by comparison with monochrome CRTs, mainly due to energy loss in the barrier coating. The differences in brightness can be compensated for the major part by varying the writing speed between colors when possible (stroke writing).

As with the beam-index tube, mechanical simplicity is obtained at the cost of electrical complexity. It is necessary to switch high EHT voltages at fairly high speeds (less than 100 ns per pixel in TV raster) and in addition the deflection sensitivity and focus change with EHT so that it is necessary to change the current conditions in these circuits. This type of tube is therefore normally operated in a field-sequential color switching mode, which complicates the equipment design and can lead to color flicker problems. For cursively written data the color can be changed between groups of characters and symbols.

+ Other color display techniques

Two other techniques which are not specific to CRTs and are applicable to a range of displays are mentioned here :

The first of these is the field-sequential color filter, described by Shanks (12). A CRT display incorporating a white or multicolor phosphor is viewed through a filter screen made of a material such as a liquid crystal, which is arranged so that using its birefringent characteristics it can be switched to pass a different color of light depending on the voltage applied to it. Such a filter permits the use of only two principal colors, and apart the loss in luminance inherent to the use of polarized light and color generation by filtration the principal disadvantages are then similar to those of the penetration tube: a limited color range and the possibility of color flicker. Difficulties have also been found in producing large liquid crystal panels of good cosmetic appearance.

Another method is to optically combine the optical outputs from two or three CRT display surfaces of different colors. The 'COMED' display (13) uses lenses and mirrors to combine a monochrome CRT and an illuminated map and a similar arrangement could be used with any display surfaces. Optical combination implies limited viewing angles and restricts its use to single or tandem-seat military aircraft, where a reduced brightness can be made acceptable by correct positioning of the exit pupil. However such a display has not yet been used in aircraft, due presumably to the penalties of volume and complexity.

3 PHYSICAL CHARACTERISTICS

The overall shape of displays using CRTs is generally determined by the shape of the CRT itself. The depth of the tube is determined by the maximum deflection angle of the electron beam, and in practice for airborne tubes this does not normally exceed 70° because of defocussing and power consumption characteristics. For a typical gun size this results in an overall tube length about 1.2 times the screen diagonal dimension (e.g. a length of 300 mm with a screen of 175 x 175 mm). The screen's usable area is less than the overall area of the front glass surface, a non-usable border of 10 mm being typical (for that size).

The narrow neck allows much of the associated electrical circuitry to be mounted within a package very little larger than the overall tube dimensions, although if vibration isolation is required this may increase the space requirement. Displays using optical components, such as head-up displays or projection displays, have geometries designed to suit the optics as much as the CRT itself.

For cockpit use, as direct view displays, screen sizes are typically in the range 50 mm diagonal to 300 mm diagonal, and are usually rectangular or square in shape. Head-up displays use circular screens up to 100 mm diameter. CRTs for helmet-mounted displays have been developed (14), and with these it is necessary to minimise both weight and size of the CRT ; a typical tube has a 20 mm diameter useful screen and a length of 100 mm. For crew compartment, tubes as large as 40 and 55 cm are also used.

EHT voltages up to 25 kV is now considered standard practice without breakdown difficulties. Similarly, the use of a large evacuated glass tube, which might be thought operationally undesirable, has not in practice caused real problems, except for larger tubes which for weight and safety considerations are better constructed using metal envelopes.

However for use in military aircraft, care has to be taken with the mounting arrangements and tubes are sometimes manufactured with an integral metal mounting collar or frame and laminated anti-implosion additional faces.

Even at the higher levels of EHT the use of lead glass faceplates generally ensures that the emitted X ray radiation is within the permissible level.

Because of the relatively large size of the tube, and the use of magnetic and high voltage components, the weight of displays based on CRTs is generally rather large. Thus for example an airborne 200 mm x 150 mm display suitable for a military aircraft could typically weigh 7.5 kg ; this could be a significant weight penalty for small aircraft and helicopters where electrostatic deflection tubes (domed mesh) become very useful in spite of their lower brightness and resolution, allowing a gain of up to 10 times in power requirement and up 3 times in overall bulk and weight in a non raster (stroke) display.

4 ADDRESSING/DRIVING

The monochrome CRT described above has a uniform screen face which can be energised instantaneously at one spot only, the position of that spot being determined by analogue currents (or voltages) in the X and Y deflection coils (or plates). Therefore to produce a complete 'frame' of information, the spot must be deflected according to some pattern, which may cover all or part of the whole screen. Upon completion of the pattern it must within a short period restart the process and write the next pattern. Because of the response characteristics of the eye the information are "refreshed" at repetition frequencies of 50 Hz or more, so that the screen appears to emit continuously and little or no flicker is perceived. Raster or stroke scanning are generally used :

a) Raster scanning

Here the spot always follows a fixed pattern of parallel straight lines, spaced closely together, to cover the whole screen area. The lines are usually horizontal and written from the top of the screen to the bottom. The picture or symbolic message is then written by modulating the beam current reaching each point on the screen. The modulation can either be simple 'on-off' to produce the equivalent of a black-white screen picture, or can be continuously varied by an analogue input signal to produce a 'shade of gray' picture.

The proposed NATO standards are either 625 lines at 50 fields per second, interlaced 2:1, or 875 lines at 60 fields per second, interlaced 2:1. The latter standard, which is only justified in aircraft cockpit use with fairly large display sizes, requires that the modulation signal has a bandwidth of 15-20 MHz if the inherent resolution of the line standard is to be used. One of the principal advantages of raster operation is that the deflection currents follow a set pattern and the deflection circuits can have a relatively low bandwidth, 50-100 kHz being typical with a high Q circuit, and this results in lower energy losses in the deflection system than for cursive operation at typical writing speeds.

As mentioned about cathode load, the writing speed in TV raster is imposed by TV standard : around 1 m/microsecond in 625 L/ 50 Hz standard.

The PPI writing is specific to raw radar and sonar data display. It is a kind of raster scanning in polar coordinates in which a radial straight line is written in synchronism with the position of the radar search beam and on which echoes appear as brighter spots. It's use is declining now as original data are "processed" and "handled" before being displayed in a more elaborate form and generally in the stroke writing mode.

b. Stroke writing

The stroke writing method allows the spot to travel over the screen face in random directions. Generally this technique is used with a fixed beam current, so that provided the spot velocity is constant the brightness of the resultant lines is also uniform. The method is mainly used for line writing (sometimes area shading). The written lines can be either straight or curved and may include a repertoire of fixed characters. There are no accepted standards, although frame refresh frequencies in excess of 50 Hz (60-70) are generally used in order to satisfy flicker perception requirements. Writing speeds depend upon the amount of data to be displayed, and are typically in the range 30-100 m.s⁻¹ whereas "settling time" of spot to within 1 % is well below 1 microsec. The need for uniform spot velocity with a randomly moving spot implies that resonant deflection circuits cannot be used and that broad-band operation of these circuits is necessary with consequent power losses. Shadowmask tubes written in raster or cursive mode merely require three modulation signals to the three independent guns. Penetration tubes written in raster mode require successive frames to be written in the selected colors. The EHT must be switched between frames with subsequent energy consumption and robust components need. In addition at frame frequencies of 25 to 30 frames per second color flicker would occur. In practice, penetration tubes are usually driven cursorily, and the added complications take the form of an EHT power supply which can switch in about 1 ms, together with deflection and focus circuits which can cope with the variations in tube sensitivity caused by the changes in EHT voltage.

5 SYSTEM INTERFACE

The information which is fed to airborne CRT displays is usually either of a pictorial nature and is derived from a sensor such as TV, Forward-Looking Infra-Red (FLIR) or radar, or is a quantitative parameter such as airspeed, height or fuel content. In the former case it is customary to select a standard display format such as the raster formats described above, and to define this as the output from the sensor package. Thus for example with scan-converted radar the scan conversion takes place within the radar and the output conforms to the display standard, thus minimising interfacing problems at the display itself.

For quantitative data it is necessary to accept this data into the display system in analogue or digital form and it then has to be converted into a form suitable for feeding to the CRT deflection and modulation amplifiers. The information may be presented in analogue or numerical form and in the former case may be as a scale, a vector or a pointer. Special interface units known as waveform generators are used for this conversion and can be made for either raster or cursive operation.

Although early waveform generators were generally made up of dedicated hardware elements to perform specific roles of character generation, axis transformation, etc, it has recently become possible to use the high speed capability of modern digital processors to carry out all the functions in a general purpose computer in which all the required characters and symbols are defined by software. The availability of large (e.g. 64K) random access memories at low cost is important in this type of design as it enables a store location to be assigned to each picture point in the display with the content of the store being updated at intervals from the computer. Modern techniques

such as this have the advantage that formats can be modified by software and as memory costs reduce even further they are likely to become the standard form of waveform generator for the future. The store is read out at fixed intervals and may be modified to improve the cosmetic appearance of lines or symbols before being converted to analogue form to be fed to the deflection and modulation amplifiers. When a combination of symbolic and pictorial information is to be presented, the appropriate signals can be mixed together either in the digital store or at the analogue stage.

6 VISUAL CHARACTERISTICS

6.1 Resolution

The phosphor screen is made up of a layer of fine granules of the phosphor material, typically of around 10 microns diameter and except in the case of the smallest tubes the size of these should not be significant in determining tube resolution. For monochrome tubes, therefore, the resolution of the image on the screen is principally determined by the diameter of the electron beam and spot-spread within the phosphor, and by the resolution characteristics inherent in the beam-writing pattern. In practice, for raster displays, these two factors tend to be approximately equal. Therefore for raster tubes operated at the TV line standards described in section 4. above, a resolution of 600-800 lines vertically is obtained and with a circular spot and adequate bandwidth in the video signal the horizontal resolution is in the region of 1000-1200 TV lines (500-600 cycles).

For signals of varying modulation level it is customary to use as a measure of horizontal resolution the modulation transfer function (MTF). Experimental measurements of MTF frequently show that the useful spatial frequency for low contrast signals is significantly less than expected from simple resolution calculations. Examples of the use of MTF methods are provided in Ref (14)(15). They indicate that the small CRTs used in helmet-mounted displays, under favourable conditions can provide up to 600 cycles per horizontal line at 50% MTF on a 25 mm diameter tube. Fig.17 shows MTF curves for larger tubes, and is taken from Banbury and Whitfield's paper (16) which provides a useful guide to the measurement of MTF of CRTs.

For cursively-written CRTs the line width effectively defines resolution, and thus is principally a function of electron-beam width and of spot-spreading in the phosphor. At the high current densities used in head-up displays, spreading can be significant, but with well-focussed tubes and at lower current densities the width of a line-pair can generally be made below that which can be resolved by the eye.

Great care must be taken on how resolution is expressed and measured. Table III shows that a ratio of near 5 is possible between different methods.

A comparison of the resolution of color CRT types has been made by Brun and Martin (17). For penetration color tubes the situation is similar to monochrome, except that the size of phosphor granules tends to be a little more apparent. For shadowmask tubes the phosphor pattern has a very real effect on resolution, especially in the case of cursively-written symbology. If a narrow line is written across a shadowmask tube, colored moiré patterns are produced at low spatial frequencies because of the discrete nature of the screen, and the electron beam therefore has to be widened to about twice the triad pitch. This could be a major problem in the use of shadowmask tubes for high resolution airborne displays. Fig 18 shows the structure of SM tubes with reduced pitch intended for high resolution (but limited luminance) alpha-numeric displays. Finally it may be noted that when lines are drawn at an angle to the scan lines on a raster display the line structure can cause an apparent series of steps in the line. Although this is an inherent characteristic of raster CRTs the effect can be minimised

by shading each edge of the drawn line on the raster lines, so that the steps are less obtrusive and the display appears to have higher spatial resolution than it really has.

Nevertheless it is generally accepted that cursively-written displays appear sharper than raster displays of lines or symbols.

6.2 Luminance and contrast

Luminance can be expressed in two ways and great care must be paid to which one is used because they are not easily compared :

Frame Luminance : A TV raster is written on the screen and the average luminance over an area covering several lines and line intervals is measured.

Line Luminance : The screen is scanned by a single line at a given speed and with a given repetition frequency. The maximum luminance of an area within this line is measured.

One of the major problems in the airborne use of CRTs derives directly from the reflection characteristics of the phosphor screen. The screen acts as a high efficiency, approximately Lambertian, reflector such that over 75 % of the light incident upon it is scattered back from its surface, and the light emitted from the phosphor is perceived against this uniform background. Again attention must be paid to which expression is considered (Fig.19). In a light ambient of 10^5 lux, the display surface can have an apparent luminance of 3×10^4 cd m^{-2} so that to obtain a display contrast of 10 the luminance of the excited phosphor would need to be 3×10^5 cd m^{-2} , a very high figure even for high efficiency phosphor. For this reason it is usually necessary with both raster and cursively-written displays to insert a filter between the screen and the viewer to attenuate the incident light before it reaches the screen ; this reduces the required luminance by a factor of 10 or more. When a phosphor with a narrow band emission characteristic is used, the filter can similarly have a narrow transmission band to achieve maximum attenuation of incident light with minimum attenuation of emitted light.

For color displays the situation is further complicated by the lower luminance levels generated by both shadowmask and penetration types of CRT. In both cases, as reported by Brun and Martin (17), TV raster operation allows contrast ratios of less than two for all colors in a 10^5 lux ambient. However by use of cursive writing it becomes possible to generate displays on a penetration tube having a contrast of 3.5 in the green and 1.7 in the red, values which indicate that the luminance levels of color CRT displays are near to being practicable for some military aircraft applications.

The contrast required for any particular display depends upon the characteristics of the displayed information and particularly upon whether the format is symbolic or pictorial. Color displays generally require less brightness contrast because they impart information via color contrast although recent tests (18) tend to show that this might be untrue with some particular colors. Head-up displays create unique problems because the symbology is perceived against a real-world background ; making allowances for the optical characteristics of the combiner, the required symbology luminance is approximately equal to that of the real-world scene so that ageing of phosphor may be observed at places where unchanged information are displayed.

6.3 Color

It is worth noting here that color CRT is the only device which can display any type of information and change its color, size or position within the acquisition time of the eye - brain system. In that respect it has no substitute in a foreseeable future.

The color of light emitted is determined by the phosphor used on the screen and as it have been said a considerable number of phosphors have been developed covering most of the visible spectrum.(Fig. 12)

The need for high luminous efficiency has caused most monochrome phosphors for airborne use to be either green or white. Several suitable green phosphors exist, as shown on the color triangle in Fig.20, and efficiencies of better than 50 lm W^{-1} are obtainable at low current density. However it should be noted that all phosphors show nonlinearities in their characteristics and the high efficiencies obtained at low current densities may fall off unacceptably at higher current levels. For example, the new rare-earth P53 can accept much higher currents than some earlier P1 and P43 phosphors although it is less efficient up to 3000 cd m^{-2} .

For color displays the phosphors used offer an efficiency significantly lower than the 50 lm W^{-1} quoted above, which partly accounts for the brightness problems described in the preceeding section. Shadowmask tubes using three colored phosphors can reproduce a wide range of colors even non spectral ones. Also shown on Fig.20 are the characteristics of P49 which is one of the phosphor used in color penetration tubes.

Color displays of both the shadowmask and penetration types have the characteristic that, because the emissions from the separate phosphors are added together at the eye, the luminances achievable at the intermediate colors are greater than at the primary phosphor colors.

6.4 Flicker

This visual characteristic is not perceived at all provided the refresh frequency of the display is kept above a critical value, typically in the range 50-60 Hz but dependent upon the lighting characteristics (19). If the persistence time of the phosphor is greater than a few milliseconds it can have a useful effect in reducing perceived flicker, although for dynamic displays it is not possible to rely on a long persistence phosphor as this will result in 'smearing'. Adjustable persistence penetration screens have proved usefull in such applications, and also for adjusting integration time of noisy signals. No EHT switching but only adjustment is then needed.

Care must be taken if the display is used in a vibration environment, since with short persistence phosphors it is possible to produce an aliasing effect due to the interaction of the refresh frequency and the vibration frequency. Short persistence phosphors also create problems when used in head-up displays incorporating cameras, and synchronisation of the camera with the display scan becomes necessary.

Particular care has to be taken to match the persistence characteristics of the phosphors used in color tubes when these are viewed in a vibration environment, otherwise a 'color break-up' may be perceived by the observer.

An extensive analysis of requirements for color cockpit CRTs as a function of human factors, technologies and intend use can be found in Ref.(3).

7 STATE OF DEVELOPMENT

The cathode ray tube is by far the best known and most widely used electronic display device, and its technical development is well established and mature. Nevertheless the particular problems associated with its use as an airborne display have resulted in a number of on-going developments intended to improve its overall performance.

7.1 Monochrome tubes are now available and in widespread use, and these generally meet most airborne requirements (20). They are typically used in cursive mode for head-up displays for daytime use, and in either raster mode or cursive mode for head-up displays in night use and for head-down panel displays. The desire for head-up display of pictorial information from FLIR sensors has led to the development of CRTs which can operate at high performance in both raster and cursive modes.

Other current developments in monochrome tubes are aimed principally at improving the contrast ratio and MTF under high ambient brightness conditions ; these improvements are being achieved through narrower beam widths from better guns, improved electron optics and better phosphors. The dispenser cathode is able to provide a higher beam current density, and because it can be manufactured to a precise shape allows the beam to be very accurately positioned within the electron optics. Particular care must though be taken with the thermal design because of the considerable heating at the electron gun.

As for electron optics, the principal improvement here is that more sophisticated magnetic focus components have been produced and that compensation can now be generated electronically using relatively cheap integrated circuit techniques.

Considerable improvements have been made in the phosphors in recent years (14), and narrow-band rare-earth activated phosphors are becoming more common. Their principal advantages are their better match with narrow-band filters intended to increase contrast and their use in combination with diffractive optic elements in head-up displays. Another interesting development is the new P53 phosphor which can accept much higher current densities than previous phosphors without saturation or damage and is therefore well suited to be used with dispenser cathodes in the next generation of tubes. Another area of phosphor development of considerable potential importance for airborne CRTs is that of transparent thin-film screens deposited on tube face by evaporation of the phosphors at high temperatures. Their transparent and non granular structure could lead to high contrast and high resolution. However they still suffer of several drawbacks: unless they are backed by a black coating, the inside structure of the tube is illuminated by incident light and "seen through", and the cathode is visible ; their very high refraction index prevents the light generated to "escape". For these two reasons (no reflective but absorbing backing and trapping of light inside the emissive layer) they presently have a poor efficiency. Besides they suffer decomposition at high beam currents and chemical poisoning problems so that further developments are needed.

7.2 Color CRTs have only recently been adopted for airborne use, initially for display of weather radar information on general aviation aircraft but more recently they have been chosen for a range of head-down displays on large civil aircraft such as the Boeing 757 and 767 and the Airbus Industrie A310. In these cases improved resolution shadowmask tubes have been used, for weather radar in a raster mode but for the large civil aircraft applications cursive writing has generally been chosen. The brightness/contrast limitations described in section 6.2 are acceptable for the lighting conditions in this class of aircraft and careful packaging and internal design have apparently reduced the vibration problems to acceptable levels. Limited use has also been made of penetration tubes in head-up displays intended as landing aids for civil aircraft. The difficulties in designing color tubes to provide a satisfactory visual display under military aircraft environmental conditions have been described in section 6. above, and the mechanical aspects were referred to in section 2. Thus far the applications of color tubes in military aircraft have been restricted to limited use of high brightness penetration tubes for daytime operation. It may be predicted that the improvements in phosphors, cathodes and electron optical design already described for monochrome tubes will also be applied to penetration color tubes to allow their increasing use in military aircraft in the future. However it appears unlikely that when driven in raster mode the brightness and contrast will be adequate for daylight use, so that the display of high resolution color pictorial information by this technique does not appear likely in the medium term.

One interesting possibility for the use of penetration tubes in aircraft takes advantage of a dual-monochrome mode of operation. Thus high-brightness green would be used for daylight operation, and low-brightness red and amber at night with the benefit of low detectability and good adaptation to scotopic vision.

As indicated in section 2.2, recent developments in the design of shadowmask CRTs suggest that these may soon be sufficiently rugged for application to military aircraft. In order to improve brightness and resolution of shadowmask CRTs solutions converting to an advantage the drawback represented by the unavoidable mask are being considered. Fig 21a) shows a design using a conventional one on which hard-magnetic barium ferrite bars are glued on either side thus focusing the (round) beam in a line shaped spot well suited for slotted screens. The mask transmission is increased by more than 50 %.

In another approach a dipolar deflection/quadrupolar focusing scheme is used (Fig.21b) it requires an auxiliary external connection. Mask transmission is said to be increased by 3 times for $\Delta V/V_0 = 2,5 \%$.

8 SPECIAL CRTs

In view of the widespread use of CRTs it is not surprising that attempts have been made to find alternatives to the conventional monochrome and color types already described. Although none of them appear likely to be competitive with conventional CRTs for cockpit use in the short or medium term, three types are briefly mentioned below which could in the longer term have some application. No description is given here of the various forms of storage tube which have been developed, since it appears that with the advent of inexpensive solid-state digital stores in digital data processing, the need to use air-borne displays with built-in storage has largely disappeared. However, it may be noted that storage tube techniques can be used to achieve extremely high brightness thanks to the continuous 'flood' of electrons impinging onto the phosphor screen. It may also be mentioned that dual-gun penetration multicolor storage CRTs have been produced on an experimental basis by Thomson-CSF.

8.1 Flat CRTs

A flat thin CRT was described by Aiken (21). The gun emits an electron beam parallel to the face of the phosphor screen, and the beam is deflected by separate horizontal and vertical electrostatic deflection plates before striking the screen. In each case the beam is deflected through 90° , the beam position and thus the spot position being controlled by the deflection plate potential. The main problem with this type of tube concerns poor focus and geometrical distortion, but as with conventional tubes, LSI circuitry offers the possibility of correcting some of the deficiencies in electro-optic performance and may lead to acceptable pictorial quality.

An interesting laboratory development has been described recently by Philips (Fig.22) in which most of the drawbacks of Aiken -and similar- flat tube seem to be overcome(22). As already seen, brightness of a CRT is related with beam current density and energy. In counterpart, the higher the EHT, the lower the deflection sensitivity. In the new design deflection and modulation are accomplished at a low energy, which permits folding the beam and locate the electron gun behind and parallel to the screen. Electrons then are multiplied in a channel plate multiplier and finally accelerated at a moderate 8.5 kV voltage. The electron multiplier, only some millimeters thick, consists of successive cavities in metal sheets set at increasing potentials up to 2.1 kV (like in a photo-multiplier) separated by glass insulation. It's size is 185 x 145 mm. An array of holes is etched at a pitch of 770 microns to form the channels. Each hole in the multiplier corresponds to an energized point on the screen so that it could be possible to make a colour tube. Total tube thickness is only 8 cm for a diagonal of 23 cm.

Sinclair in the UK have also described (23) a flat tube in a miniature portable TV marketed in 1982 ; this has dimensions of 100 x 50 x 20 mm, and the phosphor screen on the rear of the tube is viewed through a Fresnel lens incorporated into the front glass screen. Fig. 23.

8.2 Digitally-addressed CRTs

The combination of digital addressing with the high luminous efficiency of cathodoluminescent phosphors appears potentially attractive for airborne use. The most extensive development programme of a tube using such techniques was that of the Northrop Corporation, under the name "Digisplay", and has been described by Goede (24). Instead of a single scanning electron beam, the Digisplay used a large number of individual beams, each striking the phosphor layer at a fixed spot. Addressing was carried out by controlling the average intensity of the individual beams, using a series of aperture plates interposed between the large area cathode and the phosphor screen. Patterns of conducting material around the apertures were digitally addressed with 30 V potentials so that any individual electron beam can be switched on or off. It appears that the problem of matrix addressing while maintaining high brightness required the use of latching circuits which have not so far been developed and the program has been stopped.

By combining plasma discharge and digitally addressed CRT techniques, A. Schauer (25) recently succeeded in producing a tube offering high luminance, contrast, resolution, and efficiency, color compatibility, large size and slim profile (Fig. 24). Basically, the laboratory model consists of a rear chamber where a d.c gas discharge is maintained and a front acceleration chamber separated by a control plate bearing row and column electrodes. The discharge produced between the back electrode (cathode) and the row electrodes on the control plate provides the electrons which will be accelerated towards the screen after selection through holes in the control plate at row-column electrodes intersections. They will impinge on phosphors dots which may deliver different colors. The distances between cathode and control plate (25 mm) on the one hand and control plate and screen (1 mm) on the other are such that according to Paschen law a discharge cannot take place in the front chamber whereas it does in the rear one at the selected voltages (200 V and 4 kV) and pressure (1 millibar) (Fig. 25)

Many attempts have been made to excite phosphors by U.V. light emitted in gas discharges but luminous efficiency - 0.1 lumen/Watt - is much too low, whereas electron excitation of phosphors at 4 kV leads to an efficiency of 6 lm.W^{-1} and a total power requirement of only 20 W. One of the models presented has a 35 cm (14") diagonal for a total thickness of 6 cm. It displays a matrix of 448 x 720 (322 560) pixels with a horizontal pitch of 0,32 mm and a vertical one of 0,4 mm (3.1 and 2.5 dots per mm). Driving requires voltage swings of 50 V on both rows and columns and to avoid any flicker a refresh frequency of 80 HZ has been chosen so that drive electronics would have to run at 27.2 MHZ. However this figure is divided by 2 by splitting each set of electrodes in two groups and putting the drivers at both ends. Special Dimos (double implanted MOS) ICs have also been developed that properly operate the panel. Luminance reaches 200 cd m^{-2} and contrast ratio is 20:1 due to the visibility of the faint rear glow through the holes. Two half-tones are obtainable by column pulse width modulation rather than amplitude modulation which would result in non uniform currents and hence brightness (Fig. 26)

8.3 Dark trace tubes

Certain materials have the property that when struck by an electron beam they develop absorption bands in the visible wavelengths. If such materials are used in CRTs instead of phosphors, it becomes possible to write a dark line instead of an emissive line, and a CRT using this principle could be useful for airborne use although it would need separate illumination as with a conventional electromechanical instrument. Practical difficulties have so far prevented the development of viable tubes of this type; these are mainly concerned with the slow writing speed necessary with these materials (typically 2m/s) and the need to erase at a similar speed.

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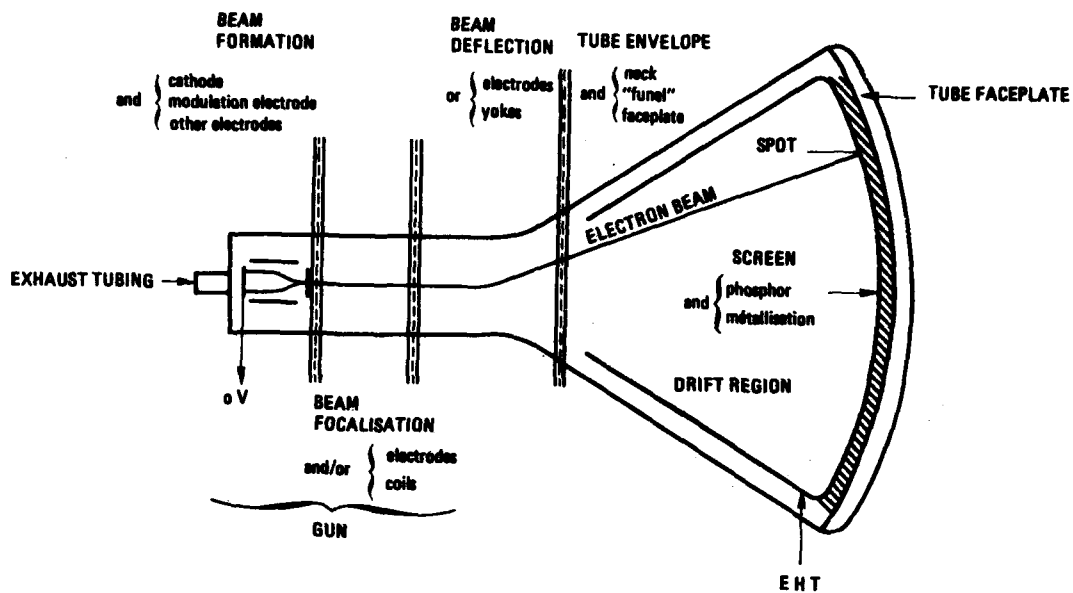
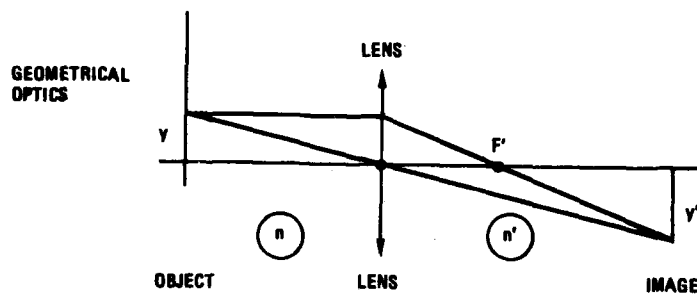
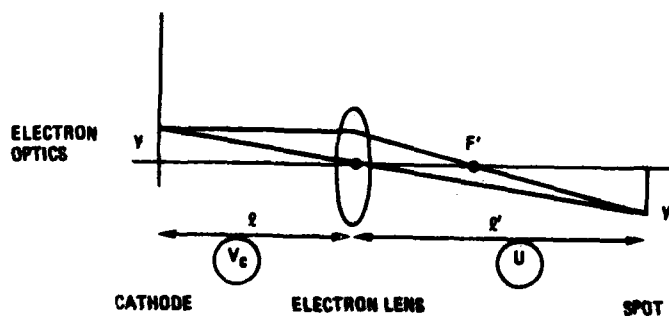


FIGURE 1 - CRT SCHEMATIC DIAGRAM



$$m = \frac{y'}{y} = \frac{n}{n'} \text{ if } n \neq n'$$



$$m = \frac{y'}{y} = \frac{z'}{z} \sqrt{\frac{V_c}{U}}$$

$$m \text{ small} \rightarrow \begin{cases} z' \text{ short} \\ U \text{ high} \end{cases}$$

FIGURE 2 - SPOT SIZE MAGNIFICATION

RICHARDSON
DUSHMANN
LAW

$$I = A T^2 e^{-b/T}$$

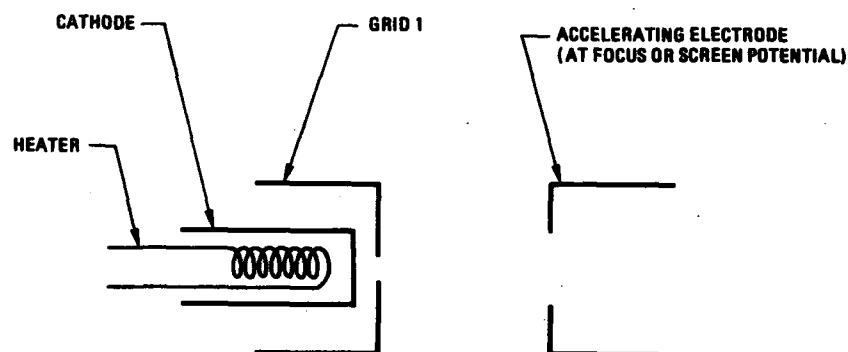
S = Cathode surface
T = Cathode temperature (in Kelvin)

$$b = \frac{q V_s}{K}$$

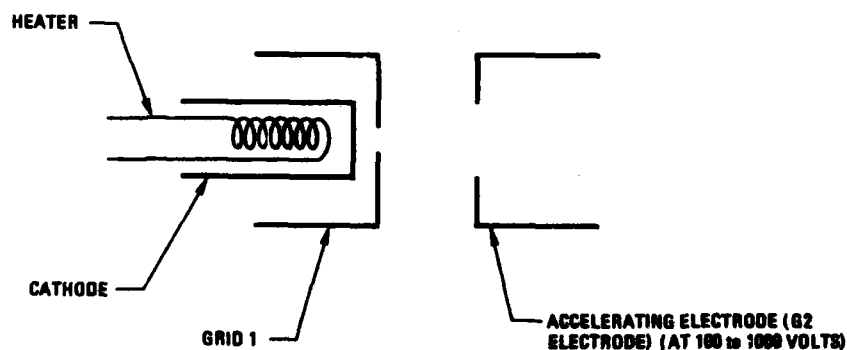
V_s = Work function of the material
K = Boltzman constant : $1.37 \cdot 10^{-23}$
q = Electron charge : $1.6 \cdot 10^{-19}$ C

		A A.cm ⁻²	b K	V _s V	Top K	I/S A.cm ⁻² @ Top
TUNGSTEN	W	60.2	52,400	4.52	2 500	2.85 10 ⁻¹
THORIUM	Th	60.2	38,900	3.35		
THORIATED TUNGSTEN	W(Th)	3	31,000	2.70	1 850	5.7 10 ⁻¹
NICKEL	Ni	26.8	32,100	2.77		3 10 ⁻¹³
OXIDES of	Ca,Ba,Sr	0.01	11,600	1	1 100	3.3 10 ⁻¹

TABLE I - CATHODE MATERIALS CHARACTERISTICS



TRIODE STRUCTURE



TETRODE STRUCTURE

FIGURE 3 - TRIODE AND TETRODE STRUCTURES

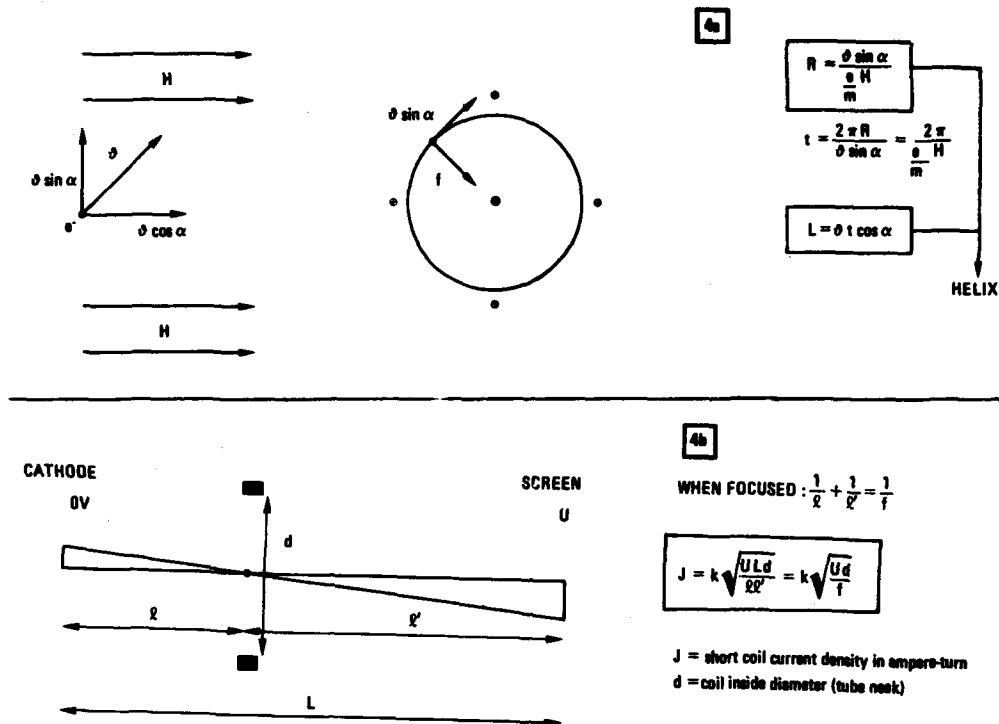


FIGURE 4 - ELECTROMAGNETIC FOCALISATION

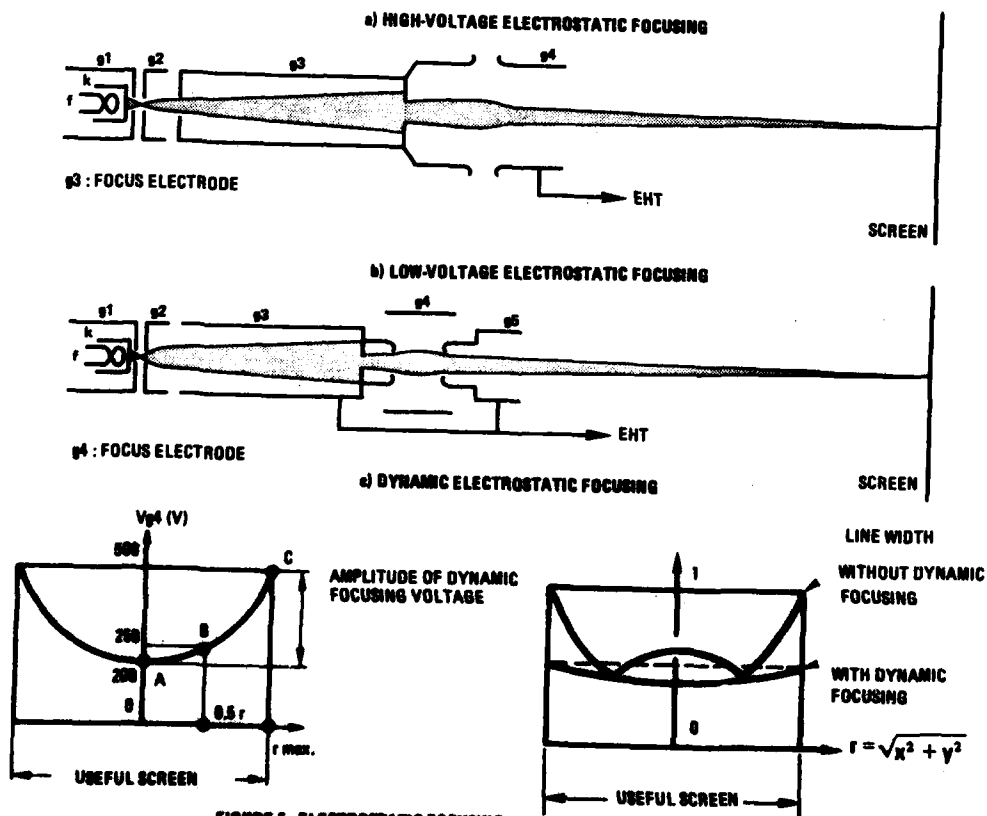
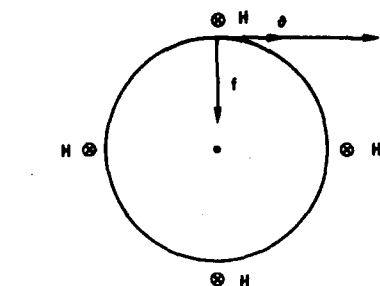


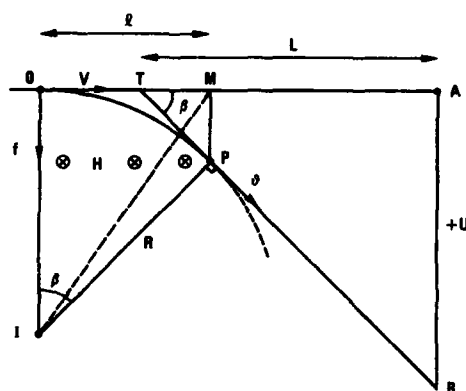
FIGURE 5 - ELECTROSTATIC FOCUSING



$$\textcircled{1} \vec{f} = -\frac{1}{r} [\vec{r}_A \vec{H}]$$

$$\textcircled{2} f = \frac{m \theta^2}{R} = \frac{m \theta^2}{R} H$$

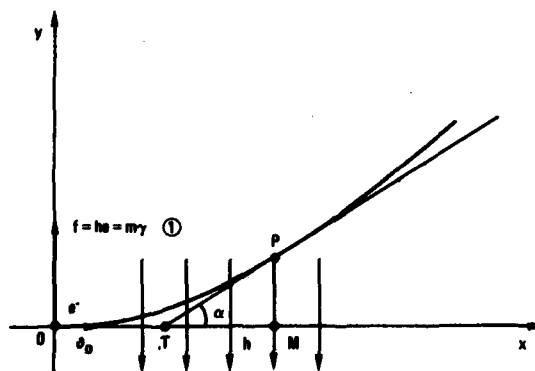
$$\textcircled{3} R = \frac{m \theta}{2H} : \text{CIRCLE}$$



L = COIL LENGTH
 L = COIL-SCREEN DISTANCE
 D = COIL DIAMETER
 J = COIL CURRENT IN A.T.
 U = SCREEN VOLTAGE

$$AB = RLH \sqrt{\frac{2}{m}} \sqrt{\frac{1}{U}} = RL \frac{J}{D} \sqrt{\frac{2}{m}} \sqrt{\frac{1}{U}}$$

FIGURE 6 - E M DEFLECTION



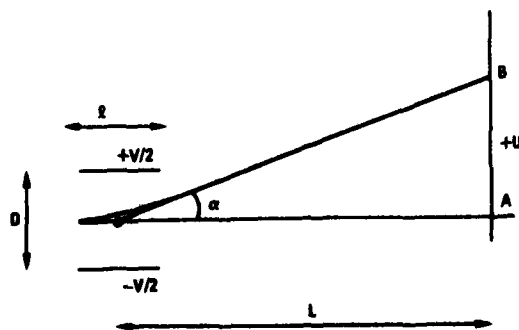
$$\textcircled{2} x = \frac{1}{2} \gamma t^2 \quad \left. \begin{array}{l} \textcircled{2} x = \frac{1}{2} \gamma t^2 \\ \textcircled{3} y = \frac{1}{2} \gamma t^2 \end{array} \right\} \text{PARABOLA}$$

$$\textcircled{1} \rightarrow \textcircled{2} \gamma = \frac{2x}{t^2}$$

$$\textcircled{3} \rightarrow \textcircled{2} \gamma = \frac{2y}{t^2}$$

$$\textcircled{4} \gamma = \frac{2x}{t^2} = \frac{2y}{t^2}$$

$$\textcircled{5} \frac{1}{2} m \theta^2 = eU \quad \textcircled{6} h = \frac{V}{D}$$



L = DEFLECTION PLATES LENGTH

D = DEFLECTION PLATES DISTANCE

L = PLATES TO SCREEN DISTANCE

V = DEFLECTION VOLTAGE

U = SCREEN VOLTAGE

$$\rightarrow \theta = \frac{1}{20} \frac{V}{U}$$

$$AB = \frac{RL}{D} \frac{V}{U}$$

FIGURE 7 - E E DEFLECTION

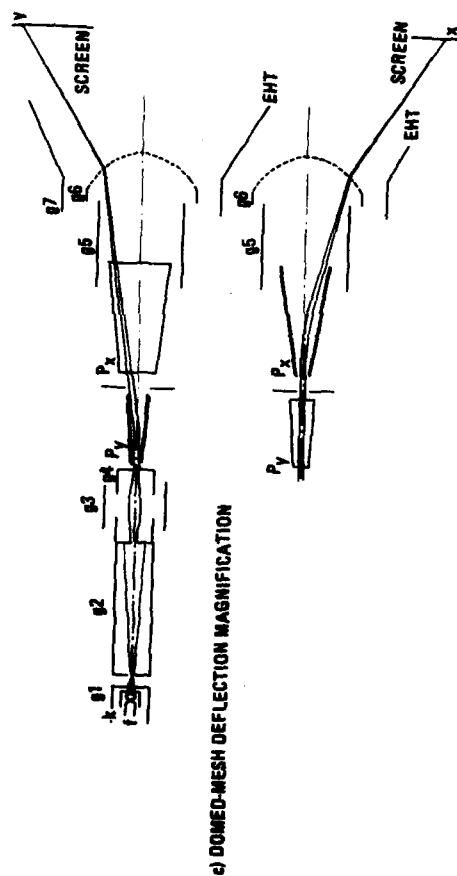
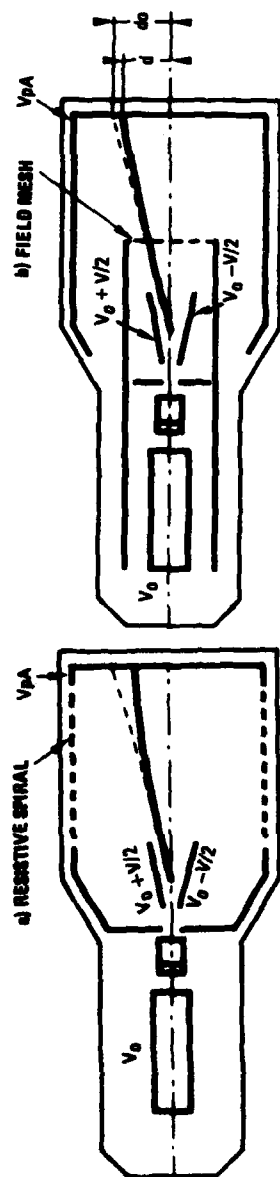
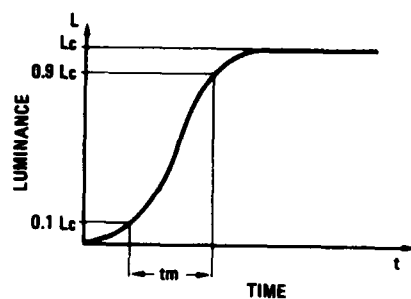
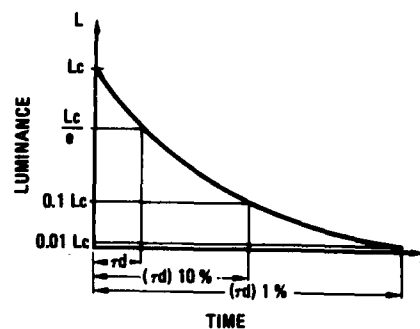


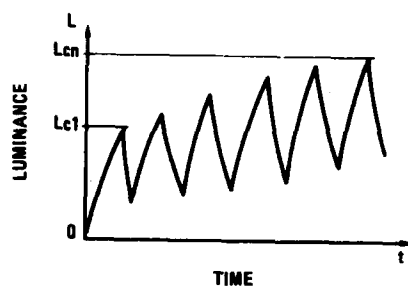
FIGURE 8 - ELECTROSTATIC DEFLECTION



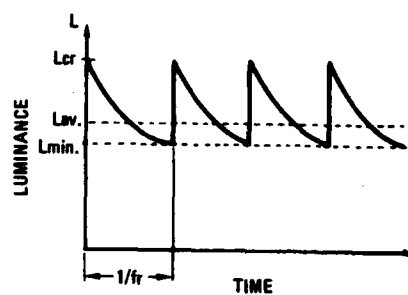
a) RISE TIME



b) PERSISTENCE



c) LUMINANCE BUILD-UP



d) FLICKER

FIGURE 9 - TEMPORAL CHARACTERISTICS

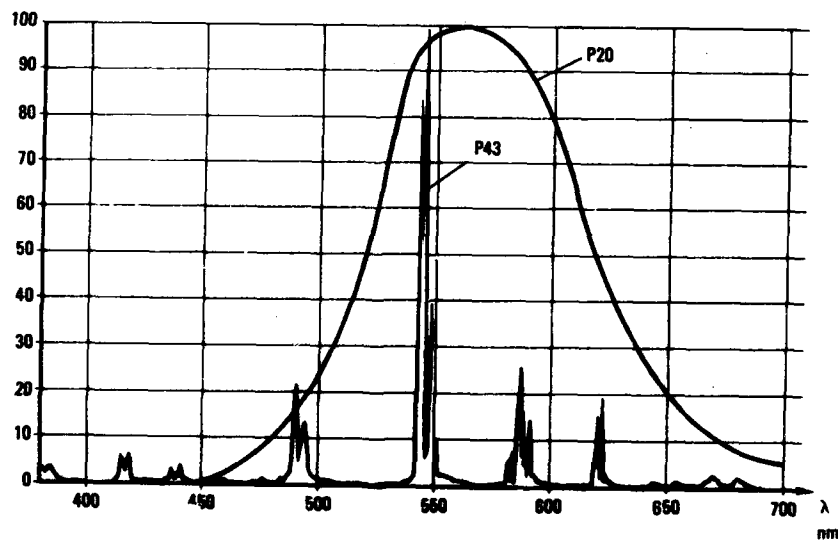


FIGURE 10 - RELATIVE RADIANT ENERGY OF PHOSPHORS

DISPLAY	PEAK LUMINANCE (fL)	MAXIMUM AVERAGE LUMINANCE @ 1/500 DUTY CYCLE (fL)	EFFICIENCY (lumens/watt)
PLASMA	7500	10 - 15	0.5 - 1
AC EL	500	1 - 5	5 - 10
DC EL	3000 - 5000	25 - 50	0.5 - 1
LED	5000	5 - 10	0.5
CATHODOLUMINESCENT PHOSPHORS	$\geq 100,000$	≥ 500	100

TABLE II - AVERAGE LUMINANCE AND LUMINOUS EFFICIENCY OF DISPLAY MEDIA

PHOSPHOR	LE (lumen/W _g)	EE (W _r /W _g) %	Eq L (lumen/W _r)
P1	28	6	470
P2	34	7	490
P11	19	14	140
P19 - P26	9	2.3	390
P20	65	14	480
P22R	12	8	150
P22V	60	15	400
P31	50	20	250
P43	41	11	370

a) PHOSPHORS EFFICIENCY

$$\frac{L}{L_0} = \frac{1}{1 + k Q}$$

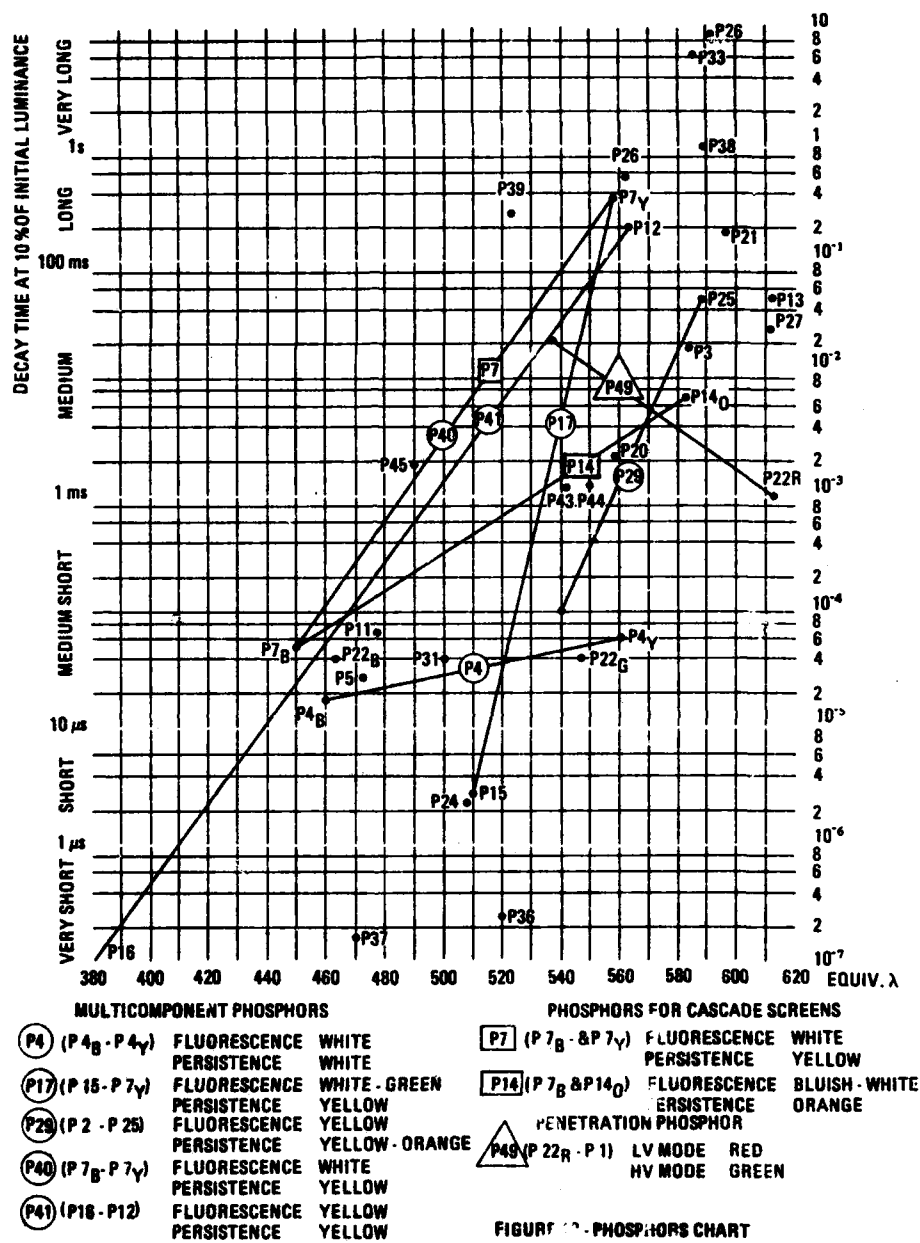
$$Q \text{ in } C \text{ cm}^{-2}$$

$$k = 1/Q_{0.5}$$

Q _{0.5} in C. cm ²	PHOSPHOR
0.1	P16 (cerium activated)
10 to 25	P2, P4, P7, P31 (sulphur)
15 to 30	P5, P15 (oxide type)
60 to 100	P1 (silicate type)
>100	P48 (penetration type)

b) PHOSPHORS FATIGUE

FIGURE 11 - PHOSPHORS



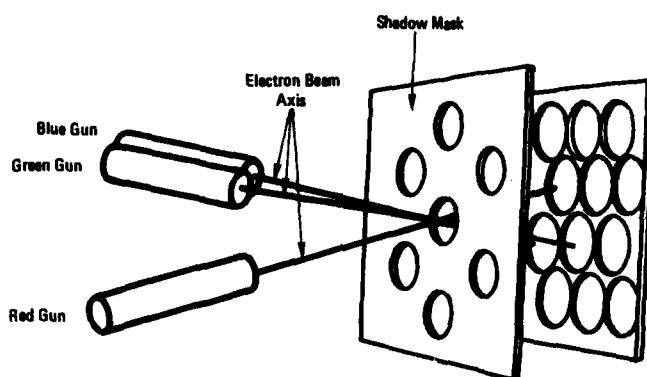


FIGURE 13 - PRINCIPLE OF SHADOW-MASK CRT

NOSC

NADC

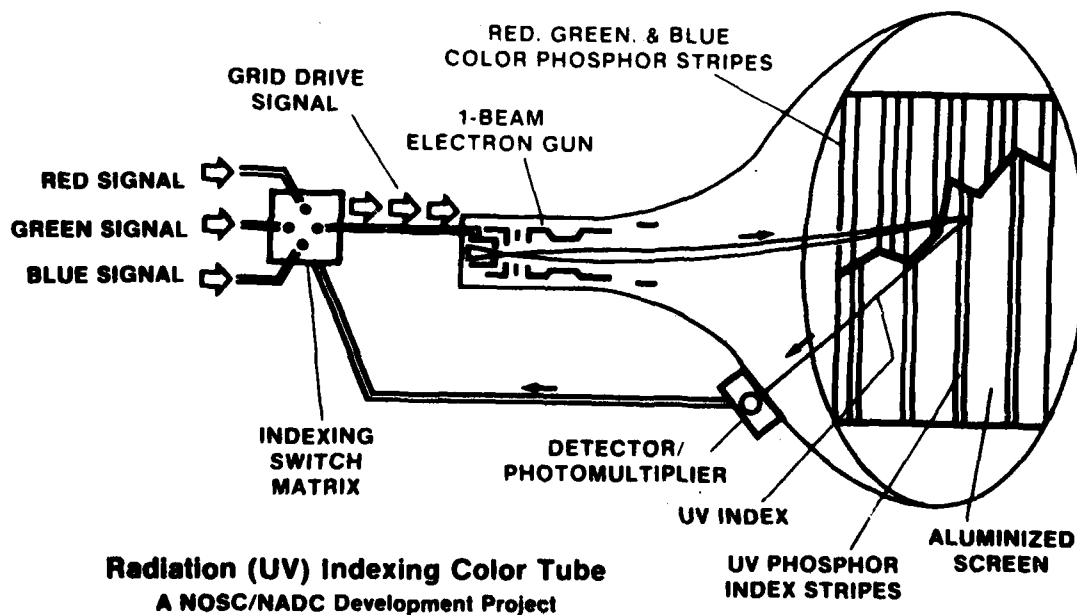
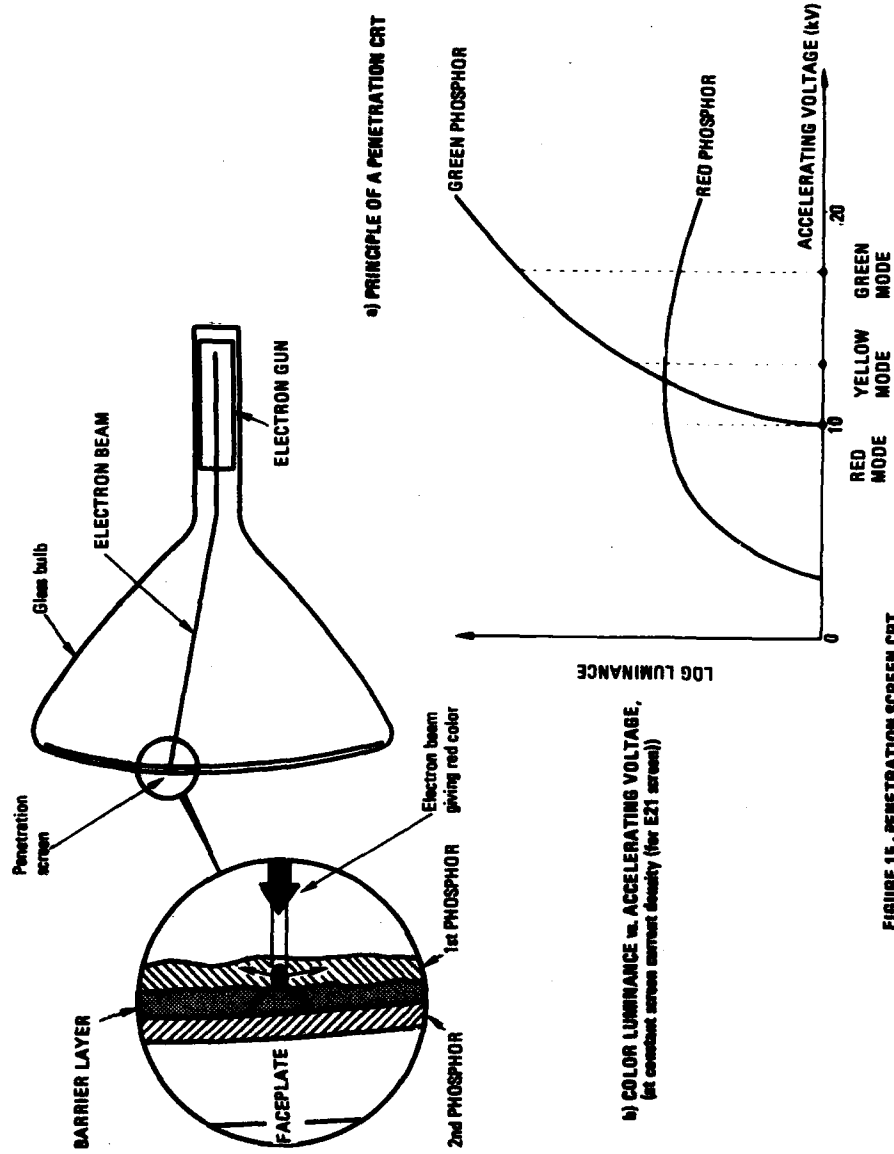


FIGURE 14 - BEAM INDEX CRT



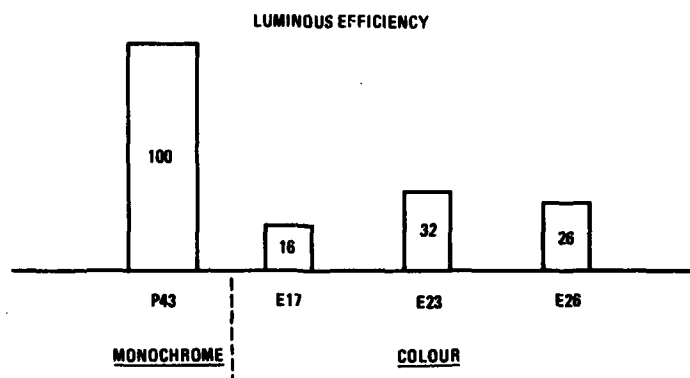
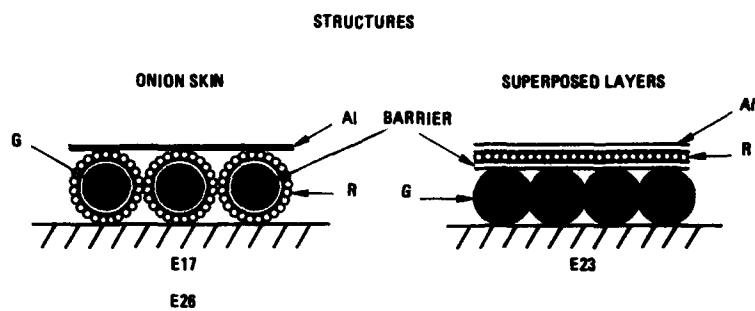


FIGURE 16 - PENETRATION SCREENS

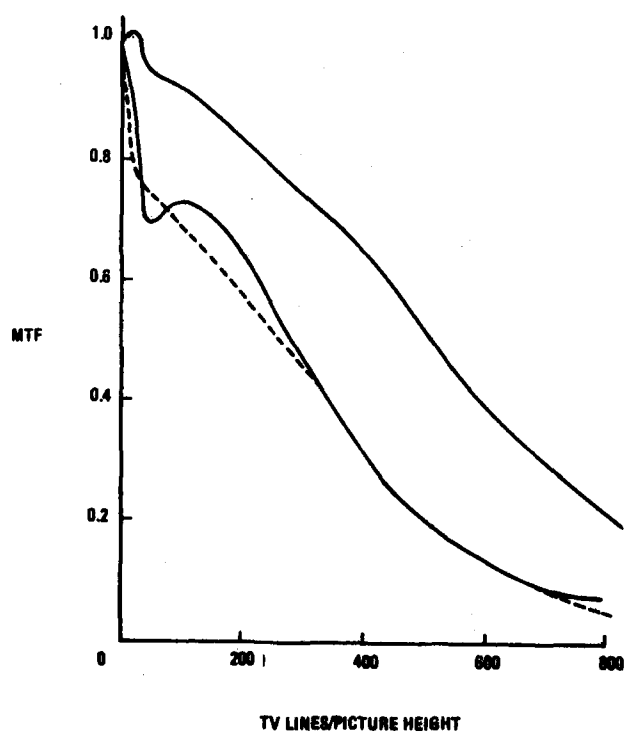
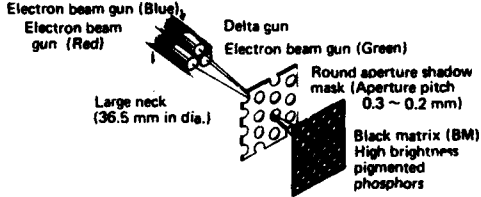
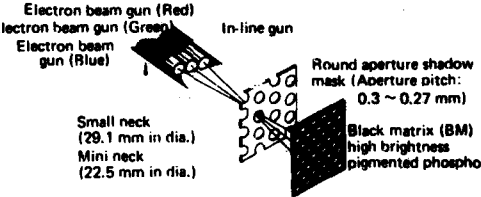
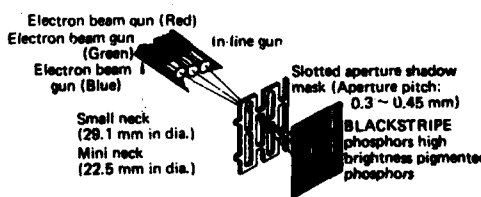


FIGURE 17 - MODULATION TRANSFERT FUNCTION

TO GET MULTIPLY BY	SHRINKING RASTER	MICROMETRIC LENS	PARALLEL SLOTS W/2	DOUBLE SLOT L/2	MTF (m=60%) m = modulation
SHRINKING RASTER	1	2	0.9	1	0.9
MICROMETRIC LENS	0.5	1	0.45	0.5	0.45
PARALLEL SLOTS W/2	1.1	2.2	1	0.9	1
DOUBLE SLOT L/2	1	2	0.9	1	0.9
MTF (m=60%) m = modulation	1.1	2.2	1	1.1	1

TABLE III - COMPARISON OF RESOLUTION MEASUREMENTS

DRL SYSTEM (DELTA GUN, ROUND APERTURE MASK AND LARGE NECK)		Typical applications
IRS IRM SYSTEM (INLINE GUN, ROUND APERTURE MASK SMALL NECK, AND MINI NECK)		<ul style="list-style-type: none"> • HIGH QUALITY DISPLAY • GRAPHIC DISPLAY • KANJI DISPLAY
ISS ISM SYSTEM (IN-LINE GUN, SLOTTED APERTURE MASK, SMALL NECK AND MINI NECK)		<ul style="list-style-type: none"> • ALPHANUMERIC DISPLAY • PERSONAL COMPUTER DISPLAY

Source JEE Sept. 62

FIGURE 18 - STRUCTURES OF COLOR CRT DISPLAY

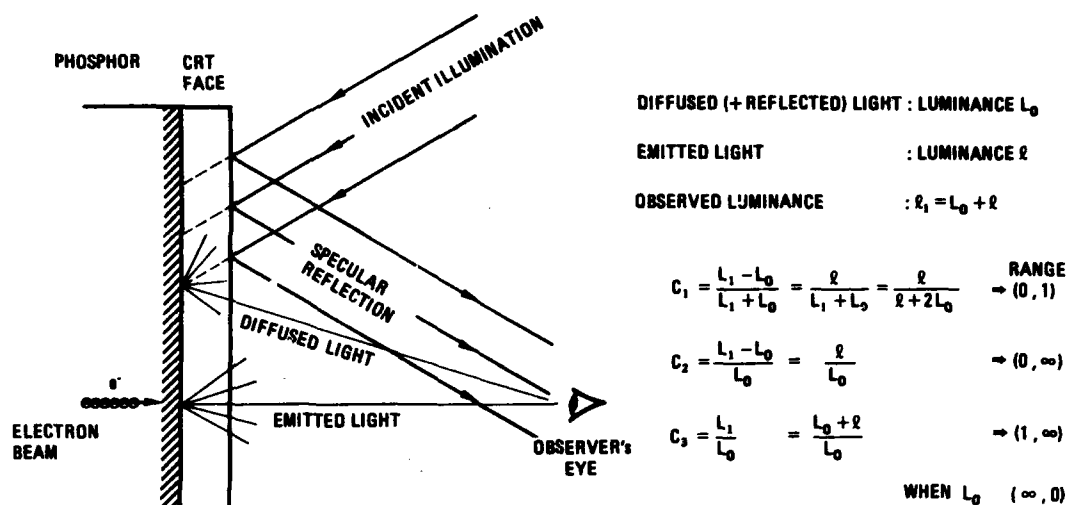


FIGURE 19 - CONTRAST RATIO

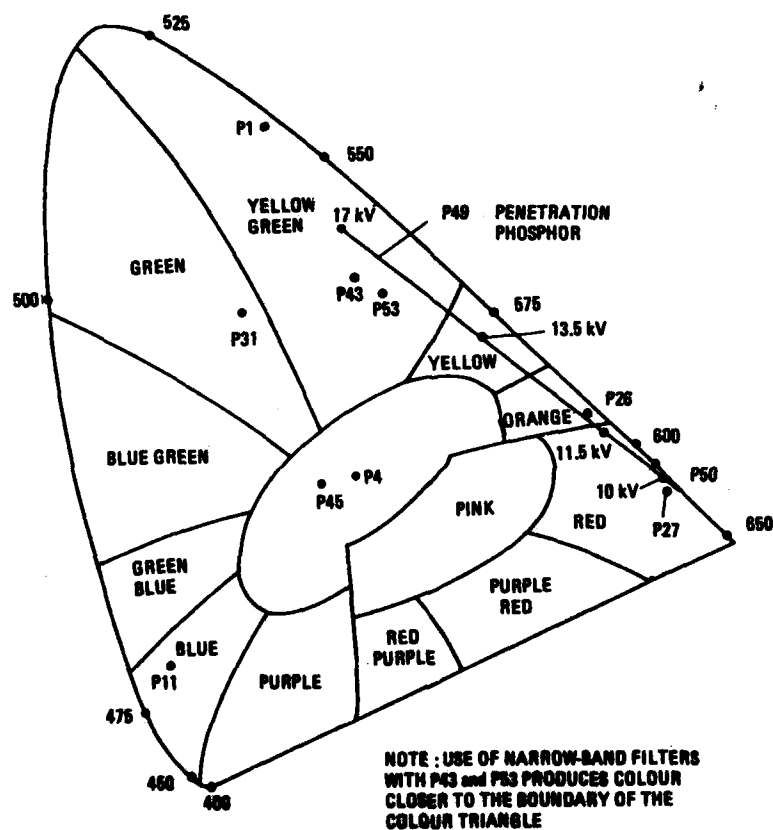
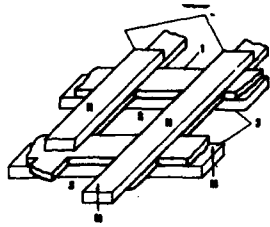
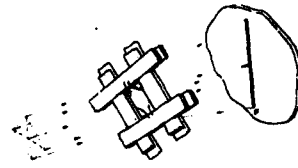


FIGURE 20 - CIE CHROMATICITY DIAGRAM



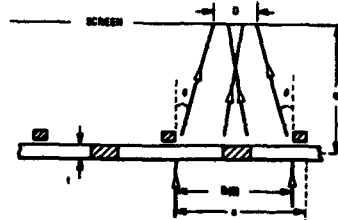
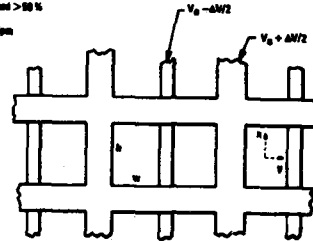
Arrows indicate the direction of the magnetic field lines, leading to north poles N and south poles S.

21a) MAGNETIC MASK (Pole)



Focusing of the electron beam is based on a two-stage lens F.

- mask transmission increased > 50 %
- conventional mask
- better good magnetic origin



21 b) DIPOLE-QUADRUPOLE FOCUS MASK (RCA)

- MASK TRANSMISSION ≈ 3
- EXTERNAL CONNECTION
POUNCE ($\frac{B}{V_0} \approx 2.5$)

FIGURE 21 - FOCUSING MASK STRUCTURES

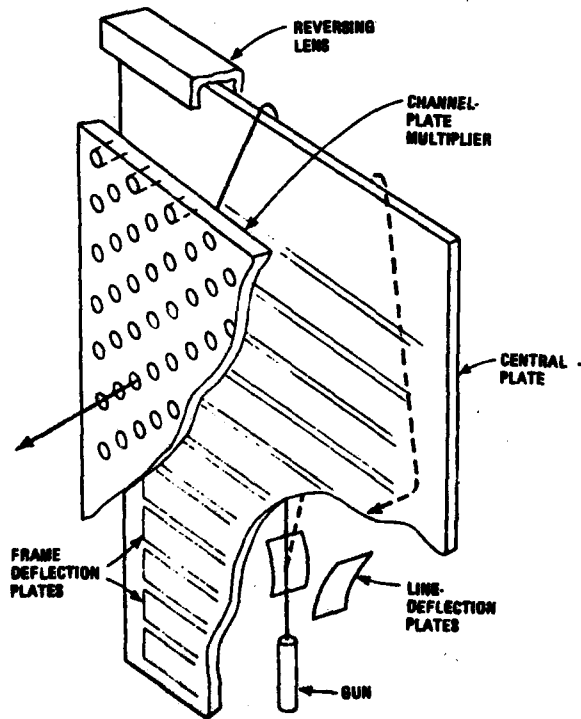


FIGURE 22 - FLAT CRT WITH CHANNEL MULTIPLIER

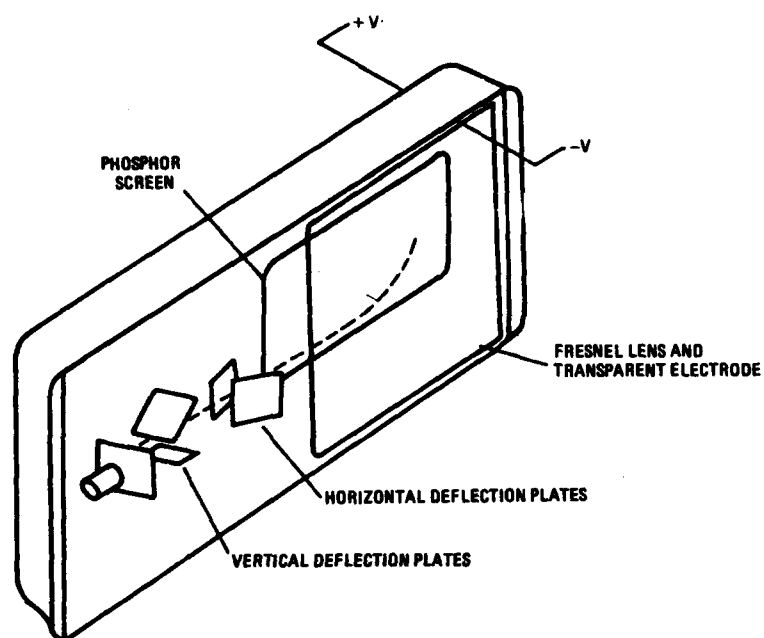


FIGURE 23 - FLAT CRT FOR POCKET TV

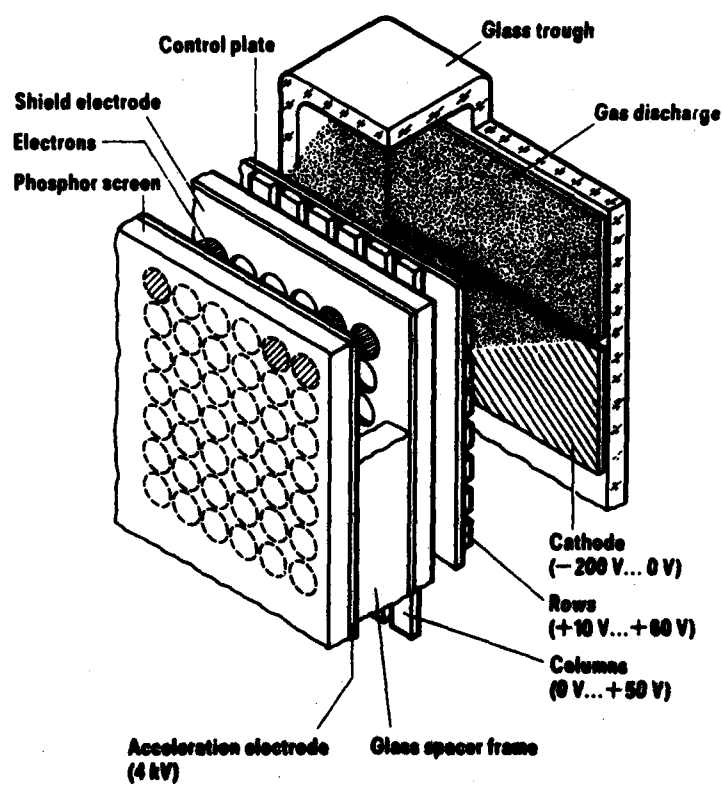


FIGURE 24 - FLAT CRT PLASMA ELECTRON EXCITED

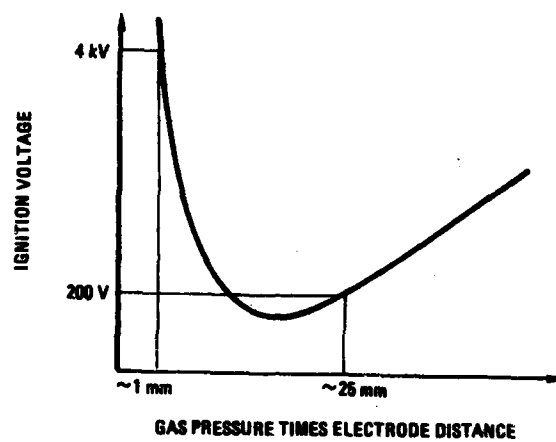


FIGURE 25 - PASCHEN LAW

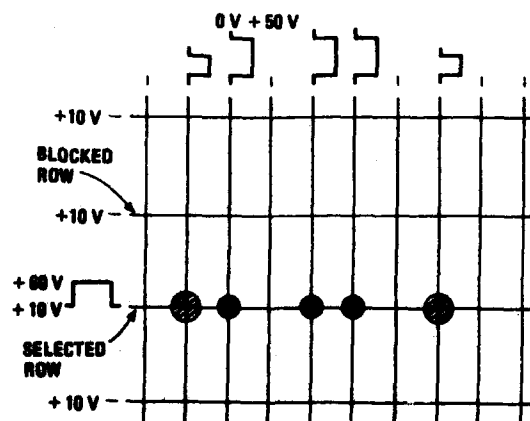


FIGURE 26 - DRIVING VOLTAGES FOR HALF TONES

IMAGE GENERATION ON MATRIX DISPLAYS

by

Professor D. Bosman
 Twente University of Technology
 P.O. Box 217
 7500 AE Enschede
 The Netherlands

5.1 SAMPLING OF THE IMAGE

5.1.1 INTRODUCTION

Images are two dimensional distributions of luminance $L(x,y)$ wherein x and y are the spatial (distance) coordinates of the local luminance L . They can be represented by landscapes with plains for uniform gray patches, slopes and hills for luminance gradients, towers and pits for speckles and dots, walls and canals for lines and vectors, and so on. The spatial resolution required for faithful reproduction of the image is determined by very steep luminance gradients and small radii in curvature of contours, (at viewing distance seen at a solid angle of 0.5 minute) and by just noticeable L -differences (JND's) in low gradients. The required luminance resolution is determined by discernible luminance contrasts (3%).

The performance and its limits of the CRT as used in both the recreational sector (television, [5.1]) and professional applications (such as aircraft displays, [5.2], [5.3]), have been extensively researched and described. The new generation of flat panel display devices [5.4], [5.5], have image generation properties which are sufficiently different from those of the CRT to require additional ergonomic investigations. In particular, the structural information (spatial domain) does not allow such operations as analogue low pass filtering based on partial overlap of pixels: the image remains tessellated because of the display technologies involved, wherein pixels are formed by reticulation of the light modulating or emitting display surface.

5.1.2 THE SAMPLED IMAGE

In a theoretical model of sampled images, [5.6], [5.7] the object or artificial image $L_0(x,y)$ can be regarded as being multiplied by a matrix $D(x,y)$ of Dirac (delta) functions located at the nodes (n,m) of a lattice or grid with spacing $(\Delta x, \Delta y)$, Fig. 5.1.a. The area $dA = \Delta x \cdot \Delta y$ centered around each node (Fig. 5.1.b) is a picture element (pixel, pel) of the object image. The grid spacing $(\Delta x, \Delta y)$ is chosen such that details of interest in the image are resolved after processing and display. Assuming that the luminance distribution over the pixel area is uniform (this being the case for most flat panel technologies) the integrated pixel luminance of the object image (volume sample) equals $L_0(n\Delta x, m\Delta y) \cdot \Delta x \cdot \Delta y$. The delta functions have unit volume at the nodes and are zero elsewhere. Each product of the integrated pixel luminance with the corresponding delta function $\delta(x - n\Delta x, y - m\Delta y)$ (which is equal to 1 at location $n\Delta x, m\Delta y$) yields one sample of the numerical representation of the image $L_D(x,y)$:

$$L_D(x,y) = L_0(x,y) \cdot D(x,y) = \sum_{n=-\infty}^{+\infty} \sum_{m=-\infty}^{+\infty} L_0(n\Delta x, m\Delta y) \cdot \delta(x - n\Delta x, y - m\Delta y) \Delta x \Delta y \quad (5.1)$$

The spatial resolution depends on the luminance contrast (section 2.2.4), i.e. on modulation depth: leading to the concept of modulation transfer function (MTF, section 2.2.1, and below). In the luminance ranges of displays, one may assume that most operations are linear. Other conditions, such as finite signal power or finite gain, usually also being met, one may apply the Fourier transform of the image or of the system image transfer (point spread) function. The two dimensional luminance distribution $L(x,y)$, transformed into the spatial frequency domain with coordinates (f_1, f_2) , can be written as the product of a magnitude and a phase spectral density distribution:

$$\mathcal{U}(L(x,y)) = M(f_1, f_2) \cdot \exp -i\phi(f_1, f_2) \quad (5.2)$$

The $\mathcal{U}(\cdot)$ is used in two-dimensional Fourier transform to denote the operation. $\mathcal{U}(L(x,y))$

is complex but $M(f_1, f_2)$, the magnitude spectral density (MSD) is real and describes the distribution of the RMS magnitude of the spatial frequency components present in the image $L(x, y)$. An example, showing the MSD of a line drawing, is depicted in Fig. 5.2. Expression (5.2), when applied to the point spread function (PSF) of an optical system, is the optical transfer function (OTF) giving both magnitude and phase transfer; $M(f_1, f_2)$ is the modulation transfer function (MTF).

From expression (5.2) one may infer that a shift of the location of a feature, if it remains well within the boundaries of the image, will not materially change $M(f_1, f_2)$ but is mostly reflected in the phase spectral density distribution. The latter thus is very important for the conveyance of spatial information to e.g. the human observer. The faithful reproduction of details of a particular object is described by the high frequency part of the MTF, irrespective of its actual location. Thus, although in the design of imaging systems attention must be paid to the OTF, in this lecture the emphasis will be on resolution and so, among others, on error sources in the MTF. The multiplication, in the spatial distance domain (x, y) , of $L(x, y)$ and $D(x, y)$ transforms into a convolution in the spatial frequency domain (f_1, f_2) . The transform of the matrix $D(x, y)$ happens to be again a matrix of delta functions, each delta function located at the nodes of a grid with coordinates if_x, if_y ; $i, j = 0, 1, 2, \dots$. The spacing of the nodes thus is $f_x = (\Delta x)^{-1}$, $f_y = (\Delta y)^{-1}$. Around each node a section is centered with area $f_x f_y$; each section carries an alias of the transform of the object image (Fig. 5.3), thus is representative for the whole of image data. The central section has node $i = 0, j = 0$: the $(0, 0)$ alias.

5.1.3 THE RECONSTRUCTION OPERATION: RECONSTRUCTION ERROR

The numerical values of the modulated delta functions which represent the sampled image determine the luminance of the fields or spots of the display, which are located around the nodes of the sampling grid. The luminance distribution of each field or spot is $F_r(x, y)$ see Figs. 5.4, 5.5.a. The actual display luminance distribution $L_d(x, y)$ is the convolution product of the numerically represented image $L_D(x, y)$ and the reconstruction filter PSF: $F_r(x, y)$.

$$L_d(x, y) = \sum_n \sum_m L_D(x, y) \cdot F_r(n\Delta x - x, m\Delta y - y) \quad (5.3)$$

The spectral distribution $\mathcal{O}\{L_D(x, y)\}$ is multiplied by the OTF of the reconstruction filter (Fig. 5.5.b). The PSF of this filter usually is symmetrical so that $\phi_r(f_1, f_2) = 0$ and the OTF equals the MTF: $M_r(f_1, f_2)$. Consequently the reconstruction filter error power spectral density is given by the difference between the PSD's $M_D^2(f_1, f_2)$ and $M_d^2(f_1, f_2)$ of the sampled, processed, image and the displayed image respectively:

$$\text{PSD}(\epsilon_r) = M_D^2(f_1, f_2) \{1 - M_r^2(f_1, f_2)\} \quad (5.4)$$

and the image power transmitted by the reconstruction filter is

$$P_d = \iint M_D^2(f_1, f_2) M_r^2(f_1, f_2) df_1 df_2 \quad (5.5)$$

Expression (5.5) shows that the aliasing error contributions in $M_D(f_1, f_2)$ (mostly 1st alias components) are attenuated, i.e. the aliasing error decreased, by the decreased transmittance $M_r(f_1, f_2)$ of the filter at high spatial frequencies: however at the expense of more omission error (expression 5.4).

The reconstruction PSF is completely determined by the display technology used, although in some cases it can be changed electronically (dither, spotwobble) to improve the visual characteristics of the reconstruction operation. In any case the sampling frequency f_d must be chosen sufficiently high to allow for the desired image quality.

In Fig. 5.5.a the luminance profiles of comparable size are depicted of a CRT spot and of a square pixel in x-direction of a flat panel display (such as thin film electroluminescence, TFEL, display). The width of the pixel equals the matrix distance Δx (in mm), its luminance is L cd m^{-2} . The corresponding display sample frequency f_d is $(\Delta x)^{-1}$; for reasons of comparison it is assumed that the CRT spot is switched off and on, so as to coincide with the locations k of the square pixel matrix. The maximum display sample frequency is determined by the max. retinal frequency resolved by the eye (2.2.2), at 70 cm (28") viewing distance this translates into 10 pixels per mm, diagonal. In Fig. 5.5.b. the cross section of the modulation transfer functions (MTF) in the $M-f_1$ plane of both the CRT spot (A) and the square pixel (B) are shown, but only for the (0,0) alias. The intersection between the (0,0) alias and the first aliases takes place at the Nyquist frequency $f_N = \frac{1}{2} f_d$. If $L_D(m\Delta x, n\Delta y)$ does not contain power in the interval $[f_N, f_d]$, then the power of the 1st aliases folded back into the interval $[-f_N, +f_N]$ is also zero. However, this is frequently not the case, so that interference occurs between image components at the same frequency originating from the first and the zero'th alias. This aliasing error, or rather what remains visible of it after reconstruction, manifests itself as recognizable interference of the deterministic features (contours, gradients) in the object image with the (periodic base of the) sampling grid or raster (Kell effect, [5.8]). Straight lines e.g. are approximated by combinations of shifted pixels and line pieces, Fig. 5.6.a. Especially when the object image contains periodic components with a main direction rotationally displaced with respect to the grid coordinates, interference fringes become visible which, in optics, are known as moiré patterns. But also (seemingly) stochastic image parts can interfere with the grid pattern to produce visibly different components.

It must be realized that there exists no inverse operation to reduce the aliasing error. Its effect can only be mollified at the expense of more blur, or by exploiting the prior information about the grid structure in combination with available quantization redundancy. For example, the experience of sculptured edges obtained in bilevel quantization (Fig. 5.6.a) can be reduced in gray level displays by softening the visibility of protruding pixels, e.g. through weighting their luminance as a function of the spatial distance error [5.9]. However, the effect is purely cosmetic, no increase of image bandwidth is obtained. Indeed, with badly undersampled images this method increases visibility of aliasing products as shown in Fig. 5.6.b).

5.2 LUMINANCE QUANTIZATION, CONTRAST ERROR

In a digital system the display converts the numerical samples $L_D(x,y)$ to pixel luminances according to some coding law. Assume that the samples $L_D(x,y)$ are words based on an interval scale, i.e. their numerical values are multiples $h.q$ of a least significant bit (LSB) or quantization interval of value (size) q . Neighbouring pixels in the display differ by at least the amount of luminance corresponding to this LSB, thus possibly adding quantization noise. For deterministic images this noise is described by a worst case error; for stochastic images by the standard deviation $\frac{1}{6} q \sqrt{3}$.

In Fig. 5.7.a a stochastic luminance signal is depicted as function of time (e.g. one line of continuous raster scanning). Also a number of quantization levels q are given, with quantizer decision levels in between; the luminance coding law is linear. If the luminance probability density would be uniformly distributed, then each quantization interval (output word) is equally likely; the average luminance equals $h.q$. With the Gaussian distributed probability density as sketched in Fig. 5.7.b, the average contrast stays the same but the probability of a quantization level to occur decreases towards high and low luminances. The probability of occurrence of a quantization level is proportional to the product of the probability density and the width of the quantization interval [5.10]. If this area is made constant, the probability of occurrence of any interval is constant, irrespective of the luminance density distribution (DD). In that case the coding law is the inverse function of the DD. What we choose depends on what we are looking for in the object image. If we expect much spatial detail at the average luminance level of $h.q$, such an inverse law (DD equalization) may be advantageous. In this lecture series it is assumed that the luminance coding law is linear and matched only to the first and second moments of the image luminance distribution. Since vision obeys the Weber-Fechner law under photopic conditions, displays are made to respond with a constant contrast interval scale. Thus visual contrast $\Delta L/L = C_{v,q}$ is constant or the luminance scale is exponential (section 2.1.2): $L_f = L_b (C_{v,q})^k$. The constant C between the $(h-1)$ th and (h) th luminance levels is $C_{v,q} = \frac{L(h)-L(h-1)}{L(h-1)}$, so the contrast ratio $L(h)/L(h-1) = C_{r,q}$ also a constant. The (10 minute of arc field) contrast JND is about 3% (ref. 2.21); choose $C_{r,q} = 1.03$. In a display with maximum contrast ratio $C_{r,mq}$, the number of obtainable gray levels on the contrast interval scale is then

$$h_m = \frac{\ln C_{r,mq}}{\ln C_{r,q}} \approx 34 \ln C_{r,mq} \quad (5.6)$$

which yields $h_m = 46$ for $C_{r,mq} = 4$; $h_m = 100$ for $C_{r,mq} = 20$ and $h_m = 155$ for $C_{r,mq} = 100$. With wordlength of b bits and linear representation of the samples $L_D(x,y)$, the contrast intervals $C_{r,q}$ are approximated to within $\pm 10\%$ for respectively $b = 10$ ($C_{r,mq} = 4$), $b = 13$ ($C_{r,mq} = 20$) and $b = 15$ ($C_{r,mq} = 100$); exponential representation yields required wordlengths of respectively $b = 6$, $b = 7$ and $b = 8$. In the average TV image, the number of contrast quantization levels used should be more than 50 (monochrome images) when subjective image quality judgment is involved; it may be considerably lower for many utility applications. For $C_{r,q} \geq 0.03$, noticeable gray scale contouring effects are perceived. However, this cosmetic undesirable effect can be reduced significantly by a number of rather simple image coding techniques which reduce gray scale gradient overload at the expense of more granularity. Abrupt jumps in the displayed image level, separated by several pixels, are replaced by jumps generally occurring at each pixel. A classical example is Robert's method in which a pseudonoise sequence (dither), uniformly distributed between $-q/2$ and $+q/2$, is added to the signal before quantization and subtracted again after quantization [5.11]. The effect is, that the representation of the local average level is improved. Adding an independent stochastic signal changes the probability distribution of the image by convolving it with the probability distribution of the added signal; thus widening this DD. Therefore, the occurrence of transitions between quantization levels is increased, thus allowing for closer fit of the spatial behaviour of the contrast. One may also say that, at the level of the quantization

interval, the local spatial correlation coefficients of the image are sufficiently decreased for the decision statistics of the quantizer to become independent of the image features.

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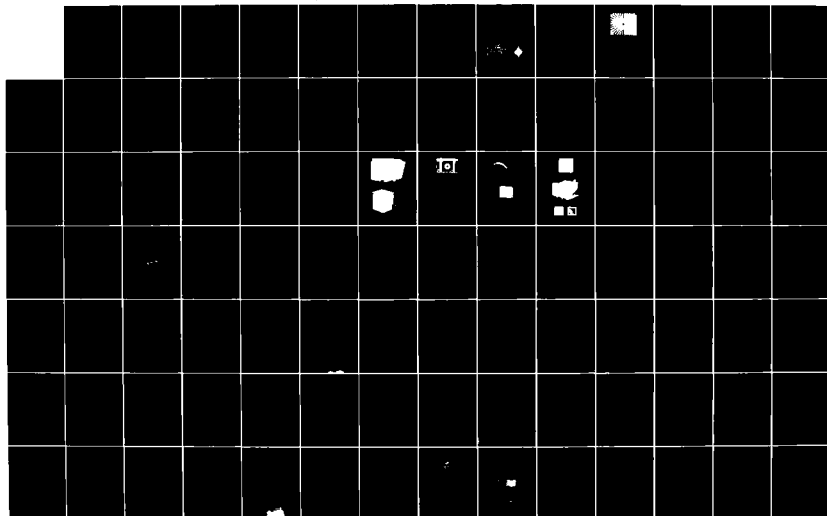
MODERN DISPLAY TECHNOLOGIES FOR AIRBORNE APPLICATIONS
(U) ADVISORY GROUP FOR AEROSPACE RESEARCH AND
DEVELOPMENT NEUILLY-SUR-SEINE (FRANCE) G H HUNT ET AL.
APR 83 AGARD-LS-126

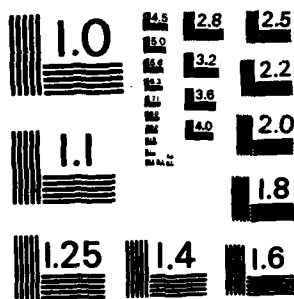
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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

5.3 ADDRESSING METHODS

5.3.1 INTRODUCTION

The two dimensional array of modulated delta functions $L_D(x,y)$ introduced in 5.1.2 (expression 5.1) exists only after the complete image has been generated and stored in the frame store. In digital sequential image displays each line consists of a number of consecutively acquired pixels, each field of a number of subsequently formed lines, each frame of a small number of interlaced fields (TV.: 2). The pixels are converted to digital format in an ADC and stored at their proper locations (addresses) in the frame store; they are updated every field or frame unless the last acquired image is "frozen".

In raster scanning (CRT, conventional TV format), the pixels are obtained by taking samples of a continuously written line. In one-line-at-a-time matrix scanning, they are discontinuously addressed areas situated along a line. The important difference between the two methods will be discussed in the next paragraphs.

5.3.2 CONTINUOUS RASTER DISPLAY, SAMPLED IMAGE

In Fig. 5.8 the European standard TV raster scan format is depicted (625 line system). The frame refresh rate is the rate at which the complete image is sampled; thus in successive images the local differences due to image dynamics are completely covered. The video bandwidth equals the product of frame rate and amount of pixel pairs/frame. One frame may consist of 2 or more interlaced fields; in standard TV systems two, one even, one odd. Each field covers 50% of the addressable pixels, but not necessarily 50% of the desired information. The number of fields times the frame rate is the field flicker frequency, which must be chosen higher than the critical flicker fusion frequency (chapter 2.2.5). The 2:1 interlacing system also can be the cause of local flicker instead of reducing it. Seldom two images 20 (16.7) msec. apart are spatially completely identical, so that local differences appear as disjoint pixels flickering at the frame (not field!) rate: correlated temporal and spatial flicker or "twinkle". Interlacing also produces other undesirable effects [5.14]; historically it was conceived from instrumental poverty, but now that the capability of electronics has sufficiently matured it should be avoided in future video/display systems.

In images which are not locked to the raster, the maximum spatial frequency which can be displayed is about one-third the number of lines per unit distance. This is for two reasons:

- first, the Kell factor of about 0.7 which applies because a horizontally oriented periodic component at about the spatial Nyquist frequency can be (partially) anti-phase with the raster,
- second, the psychological masking effect. It is found that of two periodic images of about the same spatial frequency but different modulation depths, the stronger tends to mask the perception of the other. This is so for frequency ratios between 2/3 and 3/2 [5.13].

Consequently, the maximum number of cycles to be displayed vertically is,

- in the 625 line system: $(625 - \text{flyback})/3 \rightarrow 200$ cycles,
- in the 525 line system: $(525 - \text{flyback})/3 \rightarrow 160$ cycles.

The TV raster scan image forming technique (Fig. 5.8) still is one of the principal methods. At the CRT displayface, in the horizontal (x) direction the scanning operation is continuous, in the vertical (y) direction discrete. The pixels are written in x direction convolving the electron beam PSF $F_b(x,y)$ with the modulated Dirac pulses belonging to one line l of the image $L_D(x,y)$, denoted by $L_D(x,y_l)$. In the spatial frequency domain this operation implies that the Fourier transform $M_D(f_1, f_2)$ of the image is multiplied by the beam MTF: $M_b(f_1, f_2)$. There is a (low pass) filter action: reconstruction. The associated filter error is shown hatched (/////) in the M, f_1 plane in Fig. 5.9.a. Subsequently the convolution product $L_1(x,y) = L_D(x,y_l) * F_b(x,y)$ is convolved

with the screen PSF: $F_s(x,y)$; in the f_1, f_2 plane the magnitude spectral distribution $M_1(f_1, f_2) \cdot M_s(f_1, f_2)$ results. The resulting MTF of the CRT thus is described by (Fig. 5.5.b):

$$M_r(x,y) = M_b(x,y) \cdot M_s(x,y) \quad (5.7)$$

The PSF: $F_r(x,y)$ is approximately normally distributed. The writing process equals the convolution of the sampled image $L_D(x,y_b)$ with $F_r(x,y)$ or, in the spatial frequency domain, the multiplication of $M_D(f_1, f_2)$ with $M_r(f_1, f_2)$ as shown in Fig. 5.9.b. The undesired overlap of the 1st alias is not completely suppressed. About the MTF of cathode ray tubes has been reported in e.g. [5.12].

In the vertical direction the situation is quite similar, except that the number of pixels on a line differs from the number of lines. In the CRT the scanning beam is periodically switched to a new line. The result is a series of parallel image lines with or without overlap. If one examines this result along a vertical line situated at x_k , the cross section can be represented by the operation $L_D(x_k, y) * F_r(x, y)$ which is the same as for the x direction but with index changed. The cathode ray tube makes it relatively easy to adjust the spot size so that the spatial frequency components higher than the Nyquist frequency are sufficiently attenuated. In professional tubes the $F_r(x,y)$ provides a better resolution than the available number of lines at the displayface: the present standards of raster scanning formats are line limited by the system. In CRT shadow mask color displays another source of discretization limits the resolution appreciably: the three color dots per line decrease video bandwidth per color by a factor of 3. Although individual spot size per color remains comparable, the amount of addressable spots of equal color is smaller. Again high resolution is obtainable by proper combination, i.e. operation at gray levels.

Thus the video luminance bandwidth of a color CRT is larger than the video chrominance bandwidth. This fact is not consistent with e.g. the use of color as a redundant coding attribute which must assist in rapid recognition of predominantly shape-coded symbols. However, in practice this limitation is not severe, since the resolution of the human eye for colors is also lower than for black and white; at the lower subtense limits, color symbols require about 50% larger symbol size than black and white for equal error rate performance [2.7], [2.12], [2.32].

5.3.3 THE MATRIX DISPLAY

The quantization effected in matrix display is comparable to hard-switched digitally generated TV formats without the diffuse spatial luminance transitions of the screen spot. This need not be objectionable, provided the displayed images, particularly small character fonts (e.g. 5x7, 7x9),

- are designed to match the cartesian nature of the matrix, i.e. do not require high resolution in other directions than either horizontal or vertical (no rotation!),
- are not required to travel across the display in other directions than the matrix coordinates,
- are spatially "locked" to the grid of the matrix. When that is not the case, i.e. the images vibrate with respect to the grid, individual points of the image will subsequently address adjoining points of the display grid - resulting in unsteady appearance and twinkle effect.

Of course these 3 limitations must be seen in relation to the pixel size at the viewing distance, the total number of pixels on the display area, and to the contrast sensitivity Fig. 2.4, [2.22] of the human eye. Present electronic matrix displays still have technological teething troubles and problems with drive electronics which at the moment pose upper limits (for reliable operation) to the total amount of pixels of about 50.000 to 250.000. This amount is sufficient for alpha-numerics and certain pictorial displays [5.15], Fig. 5.10, but must be considered too low for quality graphics. The state of the

art is growing rapidly and the next 5 years will show a marked improvement towards more addressable pixels per display area, as already is the case with plasma display panels.

In Fig. 5.5.a the light output distribution (B) is given of a pixel realised in e.g. LCD or thin film electroluminescent material; the associated MTF (Fig. 5.5.b) is a sinc function having its zero's at $f_d = \Delta x^{-1}$. To avoid (the display of) aliasing effects, the reconstructed optical image power spectral density should not contain components of the 1st alias in the interval $0 - \frac{1}{2} f_d$, neither components of the 0th alias in the interval $\frac{1}{2} f_d - f_d$. Reconstruction is a low pass filter action and the MTF (B) shown in Fig. 5.5.b does not help any, in contrast to the effect of the CRT spot, MTF (A), (section 5.3.2). Special interpolation schemes to overcome this drawback have been suggested [5.16].

5.3.4 LINE AT A TIME ADDRESSING

Addressing individual pixels in matrix displays is accomplished by using two orthogonal sets of parallel conductors (rows and columns) to provide e.g. a current or electric field to the display elements located at the intersections. One difficulty is obvious: when two display elements located at x_i, y_j and x_k, y_l are desired then, with simultaneously powered lines i and k , and columns j and l , two "parasitic" elements x_k, y_j and x_i, y_l also appear. This phenomenon can be avoided by line-at-a-time addressing. So, in a 200x300 element display, 300 columns are normally selected concurrently, while the 200 lines are scanned one at a time, see Fig. 5.11.a. In this circuit the selected pixels are "on" when driven with voltage $2V_D$, the non-selected (located along selected columns and non-selected lines or along non-selected columns and selected lines) should remain "off" when driven with either V_D or zero voltage. Unless the activation characteristic of the display material is highly non-linear, non-selected display elements may glow weakly also, presenting a visual noise pattern (in general non-uniform) as background glow. Thus the drive voltage V_D must remain below the display threshold voltage V_{th} , while $2V_D$ shall be larger than the threshold voltage; both observing operating margins given by tolerances of the material and of the electronics. For some materials the "on" response is proportional to $2V_D - V_{th}$, for others to the rms difference. In both cases the response is time-averaged, thus light output decreases with increasing number of lines, N . The circuit of Fig. 5.11.b provides better efficiency. In [5.17] it is shown that for rms responsive devices, the ratio of strobe voltage V_S over drive voltage V_D is optimal for factors other than 2 as used in Fig. 5.11.b. The max. obtainable ratio R for rms "on" voltage over rms "off" voltage is shown to be

$$R_{\max} = \left[\frac{N^2 + 1}{N^2 - 1} \right]^{\frac{1}{2}} \text{ at } \frac{V_S}{V_D} = N^{\frac{1}{2}} \quad (5.8)$$

This limits the number of useable lines, both from the views of voltage tolerances and of the absolute value of the strobe voltage V_S . For instance, at 1 row of alpha-numeric characters, e.g. 12 lines are required; with $V_{th} = 2$ V, $V_{rms}(\text{on}) = 2.5$ V, we obtain e.g. $V_S = 5.4$ V, $V_D = 1.6$ V, $R = 1.81$. For $N = 40$, the required $V_S \approx 30$ V. For large N , R converges asymptotically to 1: $N = 200 \rightarrow R = 1.073$.

With N lines, the light output per pixel is (time averaged) N^{-1} times the peak luminance; for fast responding materials the scanning frequency must be higher than N times the critical flicker fusion (CFF) frequency (section 2.3.3) at the experienced ambient illumination of the display. Some materials, e.g. liquid crystals, exhibit viewing angle limitations (Lecture 7) as function of the drive-threshold potential. Every effort is therefore being made to produce suitable non-linearities, either in the display material itself or through addition of one non-linear element such as a diode, a varistor or a transistor in series with each (!) display element [5.4], [5.18], as shown in Fig. 5.12.a. The latter technique is known as "active" matrix displays because it involves gain producing electronic components.

5.3.5 OTHER ADDRESSING SCHEMES

In high pixel-count displays the difficulties experienced with addressing are found on the one hand in the complexity of wiring, decoding and drive electronics, sometimes aggravated by the occurrence of high (charge) currents (with accompanying EMI); on the other hand the degradation of visual characteristics like lower frame rates (flicker) and increased viewing angle dependence (LCD's).

Active matrices have the advantage that the thresholding is shifted to the electronics (by e.g. a thin film transistor (TFT) matrix, where each transistor is located near the driven pixel); with such arrangements it becomes possible to divorce the power requirements of each display element (which is heavy in the case of light emitting technology) from the decoding electronics. Moreover, the very important attribute of memory for each pixel becomes feasible because power drain is low in the addressing side of the matrix due to the gain of the electronics. A small capacitor at each matrix node (see Fig. 5.12.b) can provide sufficient charge to keep the display element in the "on" state for the duration of the frame. Thereby the duty cycle ("on" to "off" ratio) will rise to almost 100% resulting in a much higher light output or light modulating efficiency. Simultaneously the problems of CFF and vibration induced distortions are much alleviated.

In the case of LCD, the relaxation of the requirement of full addressability has led [5.19] to an ingenious matrix addressing scheme which is both flicker free and affords the maximum viewing angle because the ratio between "on" and "off" pixel voltage is high. The penalty is the fact that only one pixel in each column may be addressed. This restricts its application to oscilloscope and analogue pointer displays.

The method makes use of the correlation properties of pseudorandom binary sequence (prbs) waveforms. Each line electrode of the display is driven by a different prbs. These have the property that the voltage difference between any two of them is pure a.c. and has a constant rms value (about 70% of the logic "1" voltage level) irrespective of which two are chosen: Fig. 5.13.b. If the i^{th} line ($i = 1, 2, 3, \dots$) has a prbs: V_i , applied and the j^{th} column also has V_j applied, the result is that the i^{th} pixel in the j^{th} column will experience zero voltage difference continuously (Fig. 5.13.a) and is "off". All of the remaining pixels in this column will experience alternating voltage differences having a high rms value and will turn fully "on". Since the prbs waveforms have only 2 voltage levels (e.g. 0V and 15V) the electrodes may be driven directly from the output of CMOS logic circuits without the need for the special multilevel drive circuits required by conventional multiplexing techniques. The display background noise is spatio-temporal random, unlike in line-at-a-time schemes where the whole display background is periodically modulated and thus can provoke a considerably intenser flicker experience. In this scheme the refresh rate of the image is equal to the repetition rate of the prbs which is, of course, inversely proportional to the number of lines (resolution) and therefore 2 to 3 orders of magnitude lower than the clock frequency of the prbs. The application of the display is limited to data with low dynamic requirements.

5.4 OTHER SCANNING TECHNIQUES

The scanning techniques of 5.3 are most suitable for processing in digital computers. This is evidenced by the fact that e.g. in some sophisticated radar systems, where the acquired image is scanned in polar coordinates, the image is first transformed to orthogonal coordinates before further processing takes place. An obvious candidate for improved image display is the hexagonal coordinate system. Of course, it does not always take a coordinate transformation to use a display format which differs from that employed by the scanning part of the system. For instance, CRT displays are not inherently confined to a display grid. One may advantageously combine the use of both raster scan for continuous images (gray scale and/or color) and random access vector scan for the generation of artificial images (arbitrary contours and alpha-numerics not aligned with

the raster).

With very large scale integration (VLSI) addressing and memory chips becoming available, also in sensors, one is not restricted to one-line-at-a-time multiplexing techniques and limited pixel storage and processing. Such new multiplexing techniques are not basically different. Their advantages are mainly the parallel processing of large amounts of imagery data in very short computation and access time.

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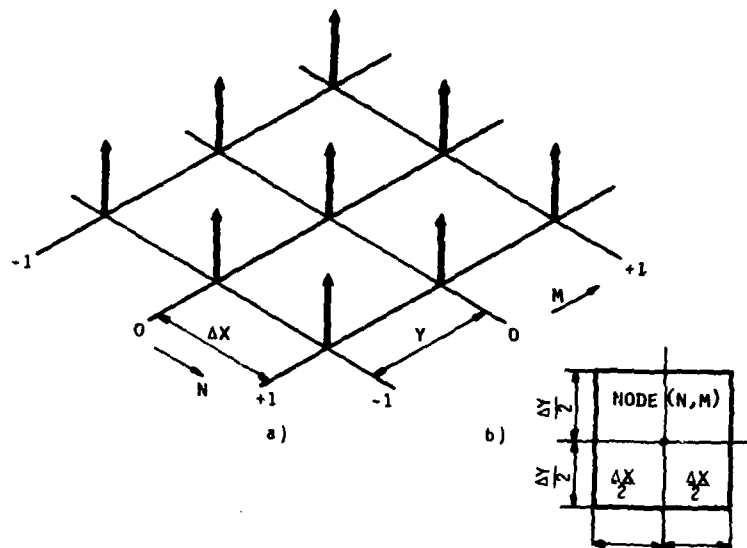


Fig.1 (a) Sampling matrix $D(x, y)$
(b) Picture element definition

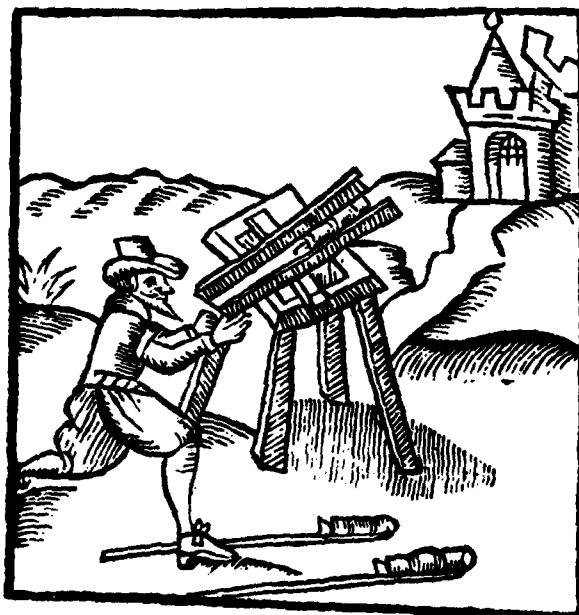


Fig.2 (a) Line drawing and
(b) its magnitude spectral density

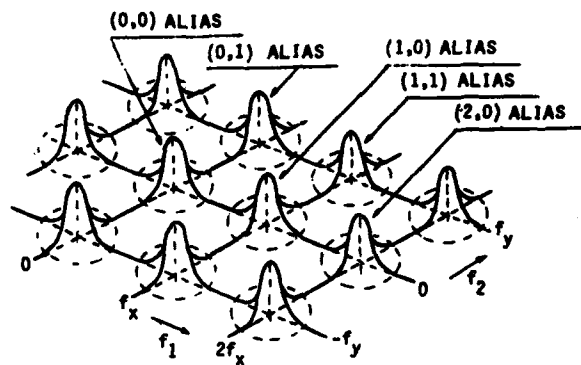


Fig.3 Fourier transform of a sampled image

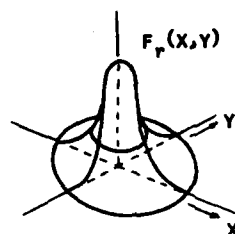
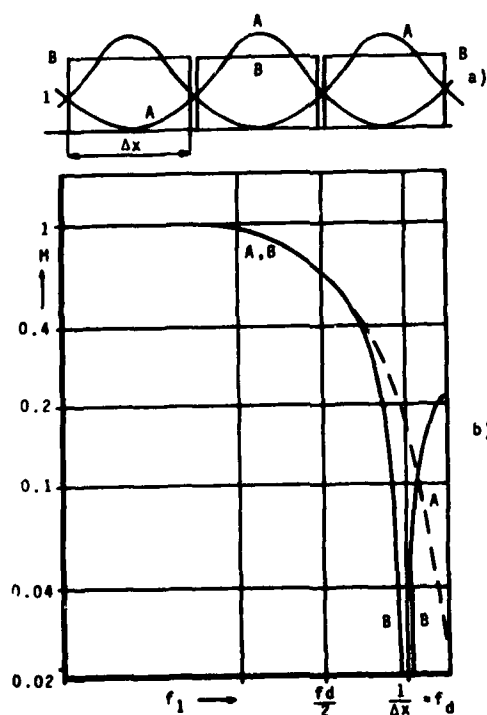


Fig.4 Point spread function (e.g. of a display)

Fig.5 (a) PSF's of cathode ray tube (A) and of a matrix display (B)
(b) MTF's to the PSF's of (a)

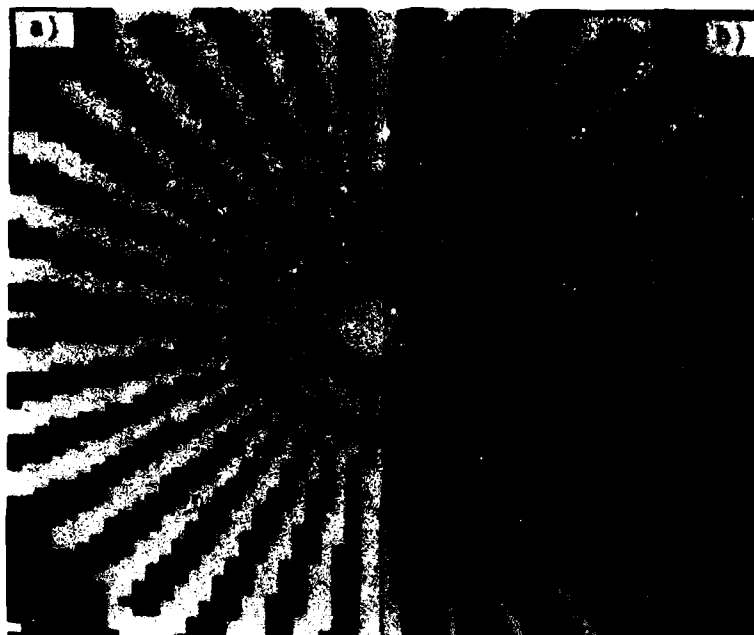


Fig.6 (a) Undersampled bilevel radial sectors
(b) Image of (a) after low pass filtering, gray level representation

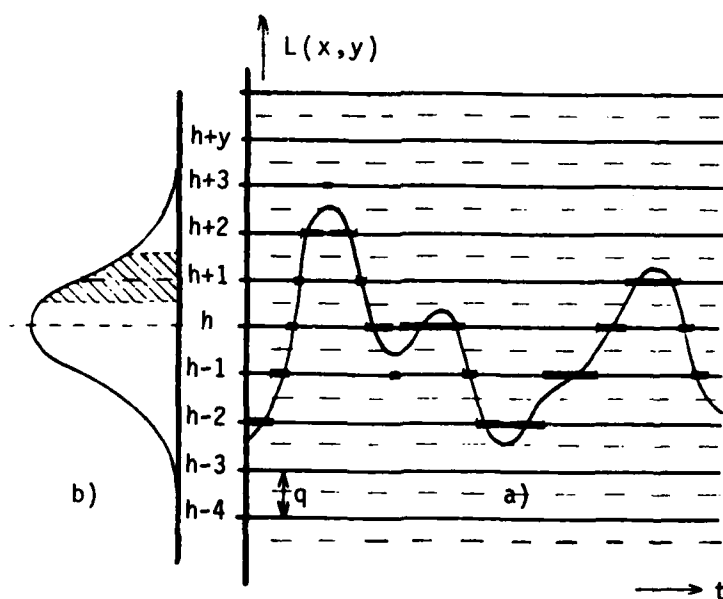


Fig.7 (a) Quantization of continuous time signal
(b) Probability density distribution of the signal; the shaded area is the probability that level $h+1$ occurs

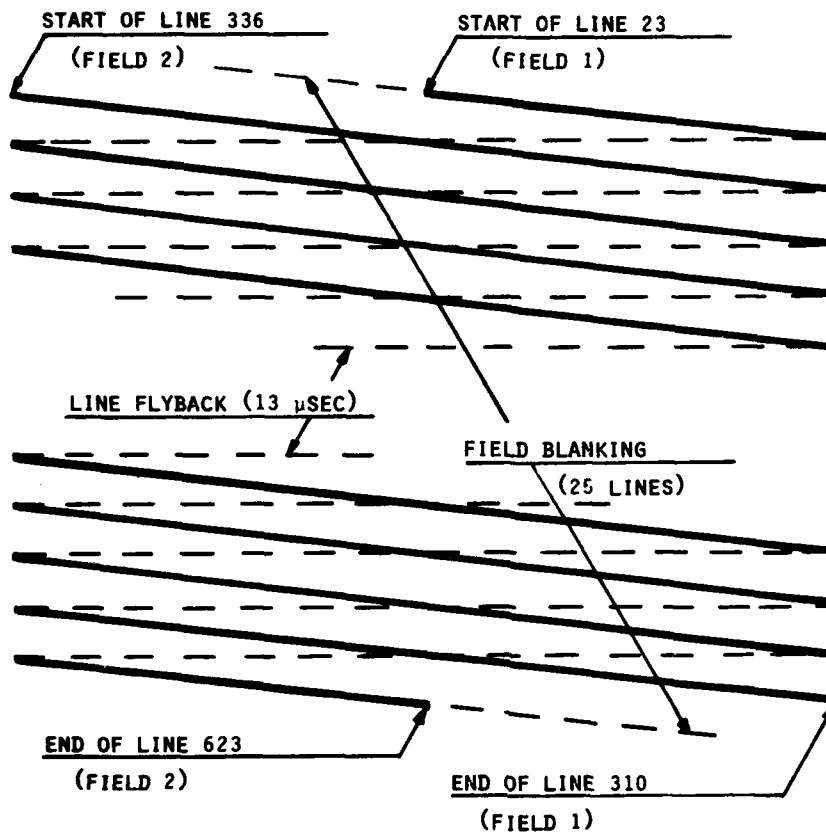


Fig.8 European standard TV raster scan format showing interlaced fields and line numbering.
 Visibility: fields 2 x 286.5 lines, line 51 microsec out of 64 microsec

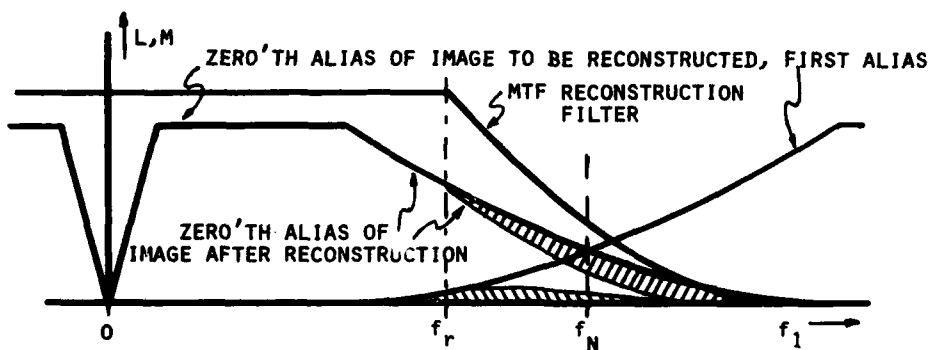


Fig.9 Reconstruction filter error //// and 1st alias error \\\ in continuous image reconstruction

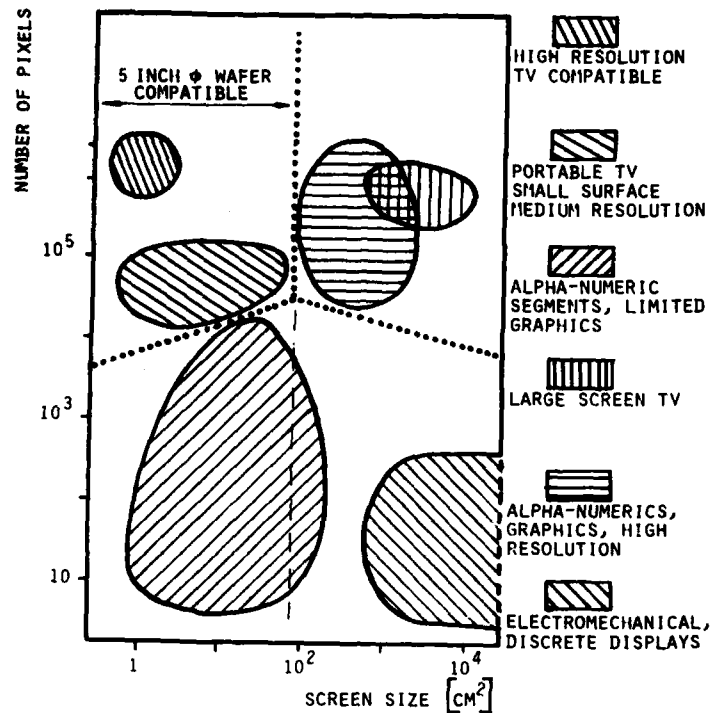


Fig.10 Number of pixels vs screensize for several application areas

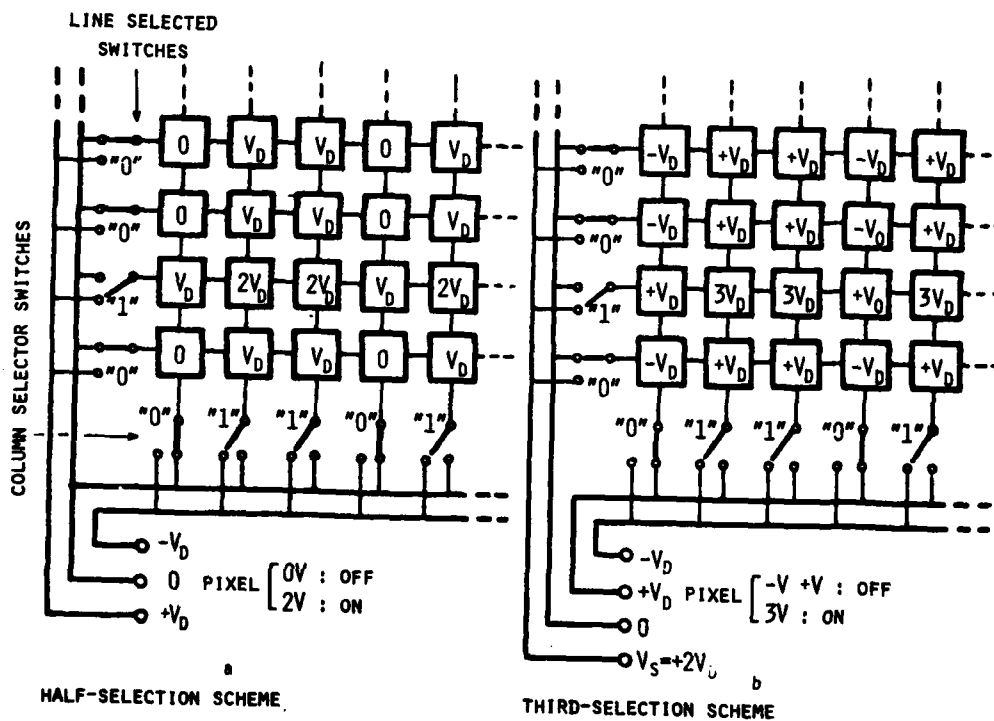


Fig.11 Display matrix scanning techniques

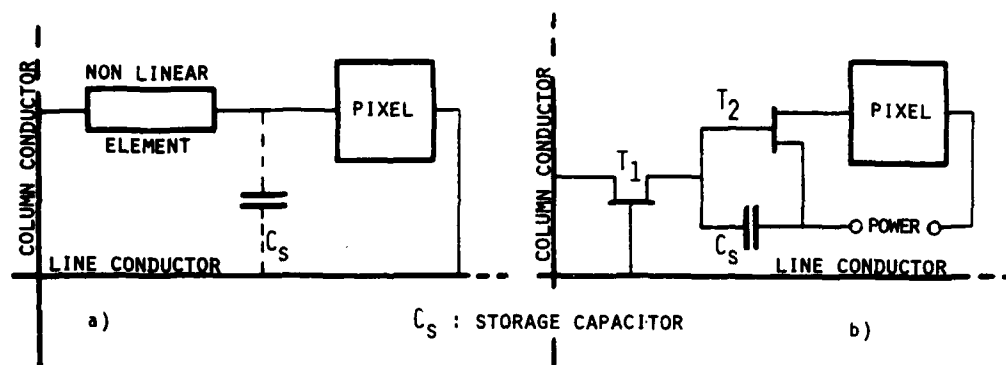


Fig.12 Addressing/drivering the picture elements of matrix displays

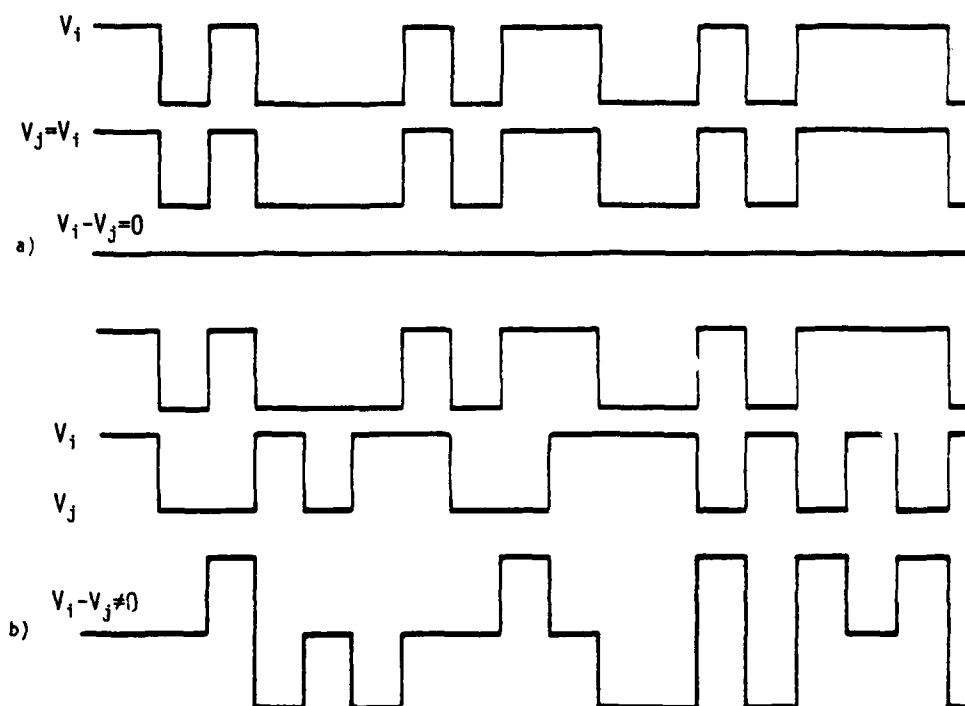


Fig.13 Waveforms in pseudo random binary sequence addressing scheme

LIGHT EMITTING DIODES

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and is given here as a supporting paper for Mr Gurman's presentation on the subject.

3.5 LIGHT EMITTING DIODES

3.5.1. INTRODUCTION

The evolution of Light Emitting Diodes (LEDs) started in the 1950's as a result of the initial search for materials suitable for the formation of improved quality diodes and transistors. A low efficiency yellow emitting silicon carbide device using an insulated metal contact to inject electrons had been demonstrated in the 1920's but its development was not pursued. The start of the 1970's marked the first real attempts to apply the research which had been conducted to the development of practical LED display devices suitable for airborne applications.

Any semiconductor having an energy band gap wide enough to support a visible radiative recombination process is a potential candidate for the fabrication of LEDs. Materials used successfully for the formation of light emitting diodes include SiC, a compound of Chemical Group IV elements, several Group III-V compounds and several Group II-VI compounds. Extreme difficulties experienced in forming pn diode junctions within Group II-VI compounds resulted in the development of a metal-insulator-semiconductor electron injection structure that to date has in general been characterised by relatively low light emission efficiencies.

Group III-V compounds turned out to be suitable for the formation of relatively efficient pn junction type LEDs. Commercial LED development was initially restricted almost exclusively to the high market volume red LEDs, with a more recent expansion into the orange, yellow and green colours, which can also be made using the GaAs/GaP system. The potential for efficiency improvements in most types of III-V compounds LEDs still remains relatively good, (ie. LEDs use high dislocation density substrates and are not optimised optically) however, a commercial product incentive for making these improvements is lacking since present devices are satisfactory except for the aircraft and military market.

In spite of the development limitations just described, LEDs have reached the point where they are being successfully applied to airborne numeric and alphanumeric display tasks with more sophisticated graphics displays designed for aircraft installation nearing completion.

3.5.2. PRINCIPLES OF OPERATION

The physics of LEDs has been the subject of a number of text books in recent years and will be dealt with only briefly here. Basically, photons are generated in a semiconductor when an electron associated with the conduction band recombines with a hole associated with the valence band. This is a non-equilibrium process and is most easily effected by injecting minority carriers across a forward biased p-n junction. To a first approximation the energy of the emitted photon is equal to the energy difference between the initial electron and hole states and must lie between 1.9 and 2.7 eV for the photon to be in the visible region of the spectrum.

The efficiency of the radiative recombination process depends on various parameters, the most important of which are detailed band structure and crystal perfection. Solid State theory predicts irradiances much greater for direct gap semiconductors than for indirect gap semiconductors. GaAs has the required direct gap band structure but its energy gap of 1.44 eV corresponds to near infra-red radiation. GaP has the required energy gap of 1.26 eV for green radiation but has an indirect gap. However, these two compounds are completely miscible throughout the ternary composition to form a range of alloys $\text{GaAs}_x\text{P}_{1-x}$. The different types of energy gap band structure and alloys with larger

phosphorous content have an indirect band structure. Diodes made from an alloy composition close to this cross-over point exhibit deleterious inter-band carrier transfer effects and optimum radiant efficiencies are obtained at $x=0.4$, which corresponds to the red displays familiar (once) in pocket calculators and digital watches.

The argument outlined above on radiant efficiencies relates to recombination processes associated with free carriers or shallow donor and acceptor levels. In indirect gap alloys in the $\text{GaAs}_x\text{P}_{1-x}$ system the efficiencies may be increased by the use of nitrogen as an isoelectronic trap. Nitrogen, being a Group V atom, should not be electrically active but the large difference in its electronegativity and covalent radius over those of the arsenic or phosphorous atom it replaces in the lattice creates a shallow trap close to the conduction band edge. Once an electron is bound in this trap the centre becomes negatively charged and can readily capture a hole in the long range coulomb potential to form a bound exciton, which decays with the emission of a photon. This process results in more than two orders of magnitude increase in efficiency for green GaP radiation at 565 nm than when nitrogen is not present. If nitrogen is in the lattice in excess, excitonic recombination at N-N pairs shifts the peak wavelength into the yellow region of the spectrum at 575 nm. A similar process, involving the "molecular" Zn_2O isoelectronic trap is responsible for the extremely efficient red emitting devices made in GaP.

It is difficult to prepare large bulk single crystals of the ternary alloys, and devices are made in epitaxial layers grown on either GaAs or GaP substrates, depending on the precise alloy composition required. Since the lattice constants of these two compounds are significantly different it is first necessary to grow a graded layer in which the initial composition is that of the substrate, and in which the phosphorous content is gradually increased until the desired alloy composition is reached. A layer of constant composition is then grown. The crystal perfection, and hence ultimate device luminescence efficiency, is a function of both the graded and constant composition layers. This explains the large differences in efficiencies reported for commercial and laboratory performance of devices, where the latter use more carefully prepared material. A summary of the range of efficiencies is given in Table 1. When corrected for the response of the human eye, the green 565 nm (0.3% efficiency) commercial LED has a luminous efficiency of about 1.9 lm W^{-1} as compared to 0.5 lm W^{-1} for the 640 nm red and 0.06 lm W^{-1} for the 698 nm red commercial devices.

Junction depths vary in the range 1-3 μm for direct gap alloys and in the range 5-25 μm for the indirect gap material. Slice processing is completed by depositing, delineating and alloying suitable ohmic contacts to the p- and n- regions of the devices.

The desired display format may be achieved with LEDs either by monolithic or hybrid construction. In the former case the format is obtained by diffusing the diodes into a single n-type substrate, which acts as the common cathode, and bringing out contacts for connecting the individual anodes to the address circuitry. In the latter case slices are diced into discrete diodes which are mounted and bonded in the required pattern onto a thin or thick film circuit board, which in most cases also contains the address and drive electronics.

In either type of display it is important to maximize the contrast ratio by eliminating visible optical cross-talk at distances of one LED or greater from the activated diode. Cross-talk out to the imaginary boundary separating adjacent LEDs is actually a benefit since it increases the area averaged (i.e. perceived) luminance of the picture element. Photons are generated isotropically across the p-n junction and, unless there is a high

TABLE 1

Efficiencies of various LEDs

Colour	Wavelength (nm)	Material	Commercial (%)	Laboratory (%)
Green	565	GaP:N	0.3	0.7
Yellow	585	GaAs _{0.15} P _{0.85} :N	0.05	0.15
Red	640	GaAs _{0.35} P _{0.65} :N	0.3	0.5
Red	660	GaAs _{0.60} P _{0.40}	0.2	1.0
Red	698	GaP:Zn,O	2.0	12.6
Red	660-670	GaAlAs		1.0

internal self absorption, those travelling through the bulk will be emitted through any convenient window for which the angle of incidence is less than the critical angle. In direct gap LEDs (eg. GaAs_{0.6}P_{0.4}) the high absorption coefficient for the emitted radiation, particularly within the graded layer, eliminates virtually all optical coupling and only the surface of the addressed diode lights up.

Although high optical crosstalk might be considered a likely consequence of the emitted photon transparency of indirect band gap LEDs, the optics of the monolithic chip geometry instead predicts that virtually no optical crosstalk should occur. The large refractive index of indirect band gap LEDs causes the critical angle to define a very small cone (ie. 34° included angle for unencapsulated GaP) through which light reaching a surface can be emitted. Due to this emission angle restriction a perfect monolithic chip with parallel surfaces could only exhibit optical crosstalk for multiple reflections of those photons which are initially emitted within emission cone windows (ie. symmetric about normals to the display surface) which have apexes located within the LED junction area. All other emissions would experience total internal reflections. The Fresnel reflections within the emission window would result in a very rapid decay of luminance with distance from the LED junction edge and visible crosstalk on the chip's planar surface would be absent. The majority of photons are emitted outside the emission window and would eventually reach the monolithic chip edges where some would be emitted but most would again experience total internal reflection. LED emissions viewed microscopically through untreated LED chip edges do in fact allow the image of the LED junction to be observed.

In practice, well made indirect band gap LED monolithic chips perform as described above with one major exception. The bulk GaP substrates are far from being perfect crystals and as a result light scattering into the LED emission cone occurs both within the bulk crystal and at its unpolished surfaces. In a darkroom lighting one LED will cause the entire monolithic chip to illuminate at a low luminance level. Under normal cockpit display contrast, optical coupling 200 μ m from the edge of an energised LED is no longer visible. The measured optical coupling distances of the indirect band gap LEDs would pose a potential image quality problem for video displays having resolutions much in excess of 50 LEDs/cm.

LED monolithic arrays intended for use in dedicated display formats can, at the design stage, be layed out in virtually any desired geometric configuration. More general

display surfaces are obtained using matrix addressable arrays in which the anode and cathode connections are orthogonal to one another.

The most difficult issue encountered in fabricating good monolithic LED arrays is achieving diode electrical isolation. Anode isolation is readily achieved since the diode junction of unaddressed LEDs are reverse biased when the addressed LED is energised. Several approaches have been used to obtain the more difficult cathode isolation. A truly monolithic process, analogous to that used in silicon integrated circuit technology, has been demonstrated in monolithic chip sizes of up to 12.5 cm square. The technique requires special epitaxial material and a complex processing schedule involving both deep and shallow diffusions. The objectives of the research, which centred on achieving cathode isolation and a flip chip electrical connection structure, were fully achieved. Further research on this LED structure is being conducted to improve it from a 25 to 50 pixel/cm resolution. The major advantage the technique will offer when fully developed is an unobscured viewing surface, since both the cathode and anode connections are made on the rear side of the monolithic chips. The latter feature is highly desirable when used for the construction of mosaic display surfaces based on the four edge abutable LED display module technique described elsewhere in this paper.

An alternative display fabrication technique which has been in use now for over ten years involves conductive epoxy bonding monolithic LED array chips to a thermally conductive electrically insulating substrate. The isolation is then achieved using a precision mechanical saw that cuts through the complete semiconductor slice and the gold surface layer on the ceramic substrate carrier. Connections to the anode rows are made either by stitch bonding or beam leading. This technique has been used with success to fabricate small single and multicolour non-abutable arrays with resolutions up to 50 pixels/cm. It has also been used for constructing large area LED displays at a 25 pixel/cm resolution.

A third fabrication technique involves the hybrid assembly of discrete LEDs using automatic die placement equipment. This approach has also resulted in successful matrix arrays up to 25 pixels/cm resolution. Luminance outputs of $17 \times 10^3 \text{ cdm}^{-2}$ are typical of recent GaP material (3.5.1) at drive currents of 0.03 A mm^{-2} leading to contrast ratios over 4:1 in sunlight.

3.5.3. PHYSICAL CHARACTERISTICS

3.5.3.1 Luminance Characteristics

Light emitting diodes produce a luminance output which is roughly proportional to the current density passing through the forward biased LED junction area. The current required to produce a desired luminance level is therefore directly proportional to the size (ie. junction area) of the particular LED being illuminated, and is the quantity which has to be controlled when using a LED as a display device. The forward biased voltage drop across a LED establishes the minimum supply voltage level needed to operate the LED (typically from 5 to 8V with voltage drops up to 3.5V) and also determines the power efficiency of the LED/driver circuit combination.

Nonlinearity in the LED luminance versus current characteristic is introduced by two effects: junction temperature induced efficiency (and colour) changes and current density induced luminance saturation. Both of these effects can result in a drooping characteristic. The temperature rise produced by the current flow is determined by a large number of thermal design factors which can vary significantly based on the layout, materials and fabrication techniques used in the construction of a specific display. The

thermal conductivity of the LED array substrate, the electrical and mechanical bonding techniques used to affix the LEDs to it, and of the ceramic/heat-sink interface are particularly important if current magnitude induced non-linearities are to be minimised.

In the family of LED materials described by the chemical equation $\text{GaAs}_x\text{P}_{1-x}$, as the fractional composition, x , of arsenic increases, both the junction temperature and luminance saturation induced non-linearity effects in the luminance versus current characteristic become more pronounced. Green 565nm GaP (ie. with $x=0$) typically exhibits a luminance characteristic which is linear in current from very near its maximum saturated luminance to near luminance extinction (ie. linearity has been tested down to $3.4 \times 10^{-3} \text{ cd m}^{-2}$ but based on LED theory should continue to decrease thereafter in a linear fashion). A junction temperature rise in a GaP LED causes a linear decrease in luminance in the -40°C to $+125^\circ\text{C}$ temperature range of nominally $0.8\% ^\circ\text{C}^{-1}$ and a $0.12\text{nm } ^\circ\text{C}^{-1}$ shift in the emission spectrum toward longer (yellow) wavelengths. As the arsenic concentration in the $\text{GaAs}_x\text{P}_{1-x}$ compound LEDs is increased the non-linearity of the luminance versus current characteristic becomes more severe at high current levels with saturation occurring gradually over a larger range of currents as the maximum luminance is approached. Red(655nm) $\text{GaAs}_x\text{P}_{0.4}$ exhibits a luminance decrease of greater than ten times that of GaP and a colour shift of $0.2\text{nm } ^\circ\text{C}^{-1}$ (nearly twice that of GaP) as the junction temperature increases. It should be noted that all of the preceding temperature sensitivities are only nominal values and will vary somewhat depending on the fabrication techniques employed.

3.5.3.2 Luminance Control Options

The nearly linear luminance versus current characteristic of LEDs, particularly at low luminance values, allows current amplitude dimming of LEDs to levels well below the 0.2cd m^{-2} level desirable for night flying or the 0.04 level needed for use with night vision goggles. The practical problems encountered with achieving these dimming levels in actual aircraft displays are those associated with implementing a current source control circuit design that is capable of handling a dynamic dimming control range of from 2,500 to 30,000 (depending on the type of display application) while continuing to look like a current source to the LEDs. A dimming control implemented to accept a digitally encoded input would for instance have to be capable of using a 16 bit binary luminance control word to avoid the perception of luminance changes as steps at the low end of the control range. Failure of the drive circuit to perform as a current source during dimming can result in luminance uniformity problems since the variations present in the knee region of the LED voltage-current characteristics can then influence the luminance produced by the LED.

The medium to low nanosecond luminance response times of LEDs also allow either or both linear pulse duration and linear pulse frequency control of LED luminance to be achieved. The response times of typical silicon integrated circuit logic and driver circuits serve as design limitations on the linear dynamic dimming ranges that can be achieved using these LED luminance control techniques.

3.5.3.3 Geometric Configuration: Small Area Displays

In small area displays, there are virtually no restrictions on the geometric configurations in which LEDs may be employed. Numeric readouts, bargraphs, scales, reticles, special geometric figures and small dot-matrix arrays can be fabricated and packaged to meet military specification environmental requirements.

At resolutions of up to 25 pixels/cm, hybrid LED arrays have been successfully formed using both semi and fully automated single diode placement and bonding techniques.

An alternative technique which has proved to be satisfactory for display resolutions between 16 and 50 pixels/cm is the manual placement of monolithic array LED chips. The chips, which typically have edge dimensions from 3 to 12.8 mm, are abutted to one another in a mosaic fashion on high thermal conductivity substrates so as to produce the desired uninterrupted resolution across the entire display surface area and are then saw cut isolated and bonded. Both construction approaches have been used to produce military specification qualified LED arrays, with the monolithic approach used at resolutions of up to 46 pixels/cm, for HMD and film annotation applications.

As is the case for virtually all electronic displays, the overall design of a LED display system must be carefully optimised to produce a result that will be considered satisfactory by a pilot. In the case of LED head-down direct view displays, this requires that special attention be paid to the optical filtering, the electrical drive/address techniques employed and to the thermal design.

Overall display system design optimisation is equally critical when attempting to employ a LED display as an image source for a helmet mounted display application. (See section 3.5.7.2). In this case heat dissipation, weight and volume impose design restrictions. In addition, the luminance required of the image source is critically dependent on a variety of design factors only indirectly related to the LED. These factors for instance include: the image combiner field of view, the exit pupil size, the quality of the image combiner narrow band interference filter (which reflects the LED light with minimal blockage of the background scene), the transmittance of the high ambient light visor, and the scene luminance level when the pilot changes to the clear visor.

3.5.3.4 Geometric Configuration: Large Area Displays

The low operating voltages associated with dot-matrix LED displays require that increased average drive currents be used if the displays are to be operated at the same power levels as other higher voltage displays. Short low-resistance current leads are therefore necessary to minimise lead losses and to provide the near negligible voltage drop, between the LED drivers and the addressed dot-matrix picture element (pixel), that is required to produce displays which have a uniform luminance distribution across the entire surface. The method used to achieve this objective and still be able to have large-area LED head-down displays is to form the display surface using a mosaic of edge abutable independent display modules, each having its own set of integrally mounted drive and address integrated circuits.

The first successful large area LED graphics display to be constructed using the modular building block approach was completed in 1978 (3.5.3). The display has active area dimensions of 10.4x7.8 cm and consists of four green emitting two-edge abutable LED modules mounted side by side to form the display surface. Each module consists of a ceramic substrate of the same width as the LED surface but 13.3cm long and 0.1cm thick with a nominal 25 pixel/cm green emitting LED array of 2.6x7.8 cm dimensions centred on the ceramic and having its column driver hybrid integrated circuits mounted on the rear surface. The objective of this display was to allow evaluation of the feasibility of integrating the LED, optical filter, ceramic, metallurgy and silicon integrated circuit technologies required to build modular LED displays suitable for use in portraying real-time flight control information to a pilot. Based on the success of this concept demonstration display, a programme was initiated to develop flightworthy graphics displays utilizing a full four-edge abutable module.

Figure 3.5.1 is a photograph of a green emitting, nominal 25 pixel/cm resolution, GaP LED display module. A heat sink serves as the basic structural element for the module to

which the LED display surface ceramic substrate, driver substrates, connectors and a power line filter capacitor are solidly attached. The display module is a cube having about 2.6 cm edge dimensions. The modules are designed to permit their individual removal or replacement in the display mainframe. Figure 3.5.2 is a photograph of an operating 13x10.4 cm active area LED display formed with a mosaic of 4x5 four-edge abutable modules of the type shown in Figure 1.

The size of the standard module was selected to accommodate either a 64x64 pixel, nominal 25 pixel/cm resolution graphics LED array or a 128x128 pixel, nominal 50 pixel/cm resolution video LED array where the binary equivalents $64=2^6$ and $128=2^7$ are compatible with standard silicon digital drive/address circuitry. The choice between different digitally compatible module sizes represented a tradeoff between minimising the total number of modules to display mainframe electrical connections, in large displays, and achieving a module small enough to permit reasonable flexibility in the dimensioning of displays built using the modular building block approach. The ultimate maximum size of a module is limited by the current sourcing and sinking capabilities of the modules silicon integrated circuit drivers.

The primary performance advantage gained from using modular display construction stems from the fact that the image legibility of the complete display is the same independent of the number of modules used to construct it. This follows because the display modules are all updated with information in parallel (i.e. at up to their 500 Hertz refresh rate capability) with each module acting effectively as an independent display. As a result, display size does not influence display maximum image speed, image quality, image positioning accuracy, emitted luminance, contrast, or viewing angle, since these quantities are known and fixed when the display module is constructed. An in-depth discussion of both the advantages and disadvantages of modular flat-panel display construction is contained in Reference 3.5.4; see also paragraph 3.5.4.1.

Although designs for LED displays having up to 13 cm x 13 cm active areas with just slightly over a 2.5 cm depth have been formulated for display locations in front of head-up display optics, the large area LED displays demonstrated to date have had an approximately 7 cm depth. This depth would not be expected to increase for larger area displays, where display surface areas of up to about 20 cm square are presently being considered.

3.5.3.5 LED Failure Mode

LEDs have two potential failure modes. Under the forward biased light emitting drive condition, excessive drive current densities can result in junction temperatures rises which permanently alter the diode luminance/current density characteristics, or for extreme overdrive conditions can destroy the device. Junction temperatures above approximately 200°C, whether induced through driving the LED or by elevated ambient temperatures, can cause this type of degradation in green GaP LEDs. In general, increasing arsenic compositions in the $\text{GaAs}_{x-1-x}\text{P}_{1-x}$ tertiary compounds causes the temperature limit to be reduced. When adequately cooled the GaP LEDs can tolerate continuous current densities of up to about 200 A/cm² without damage and higher levels in a pulsed drive mode. Comparing this drive limit with the 1.5 to 3 A/cm² maximum current densities needed to satisfy practical aircraft dot-matrix display applications, explains the large tolerance the displays exhibit in the presence of inadvertant short duration overcurrent or timing fault induced 100% duty cycle drive conditions.

The second potential LED failure mode occurs when the reverse bias breakdown voltage limit of the LED is exceeded by a sufficient amount. Depending on the diode fabrication techniques used, either the Zener or the avalanche multiplication mechanisms (that are

made use of in silicon Zener diode applications) will be operative.

Both types of potential LED failure mode can be completely avoided through proper design of the LED display. The excellent reliability record of LEDs in practical display applications is testimony to the ease of eliminating these failure modes.

3.5.3.6 Luminance Degradation

Luminance degradation as a function of operating time cannot be avoided. All of the present light emitting display technologies including CRTs, plasma panels, EL panels and LED panels exhibit some degree of luminance degradation as a function of operating time. For LEDs operated near their current density/junction temperature limits, the half life (time to degrade to half the initial luminance value) of the LEDs is about 15,000 hours for GaP liquid phase epitaxial LEDs and is 25,000 hours for GaP vapor phase epitaxial LEDs. Red LEDs typically exhibit somewhat shorter half lives under the same operating conditions.

The half life of LEDs increases significantly with reduced junction operating temperatures and current densities, with the temperature of the diode junction playing the most important role. As an illustration of this, half life tests run on continuously scanned XY matrix arrays of green vapor phase epitaxial LEDs for a period of five years (ie. 43,800 hours) predict luminous half lives of at minimum 500,000 hours. The 25 pixel/cm LED arrays used for these tests were operated without heat sinks and using drive conditions consisting of 500Hz refresh rate current pulses of 100 mA amplitude and 10% duty cycle in a 25°C ambient temperature environment. This drive condition is equivalent to that used for the graphics portrayal LEDs built to date with the exception that the test uses a factor of 20 higher pulse duty cycle in order to stress the array.

3.5.4. ADDRESSING/DRIVING

3.5.4.1 Addressing Techniques

Lacking either inherent memory or a convenient method of either forming or incorporating an active control drive at each LED location, the most effective method available for activating LED displays is through parallel sequential scanning of data onto the display. When displaying segmented characters (such as numeric readouts) the readouts are typically scanned so that all of the data needed to describe each character to be displayed is provided in parallel as each readout location is sequentially scanned. On dot-matrix LED arrays layed out on orthogonal axes, this time sequenced scanning technique is referred to as matrix addressing where data is entered and displayed one line at a time.

When dot-matrix display arrays of greater than 2x2 pixels are to be addressed, a saving in the number of drivers and a reduction in the number of address lines is achieved when matrix rather than direct drive addressing is used. It can moreover be shown that an array of $N=n_x \cdot n_y$ pixels, where n_x is the number of columns and n_y is the number of rows, will require the fewest number of drivers, $n_x + n_y$, if the number of columns equals the number of rows. This is also considered in Section 2.

3.5.4.2 Constraints on LED Array Size

The total time averaged current, I , required to drive an individual LED at a specified luminance level is the same independent of the addressing/driving technique employed to operate it. This implies that in a dot-matrix array of n_x columns and n_y rows and

containing $N=n_x \cdot n_y$ total pixels, drivers employed in a matrix addressing approach would have to have a time averaged row current drive capacity of $NI/n_x = n_y I$. In addition, either the row or the column driver circuits must be capable of handling a peak current pulse amplitude of up to n_x times the average row driver current, that is $n_x^2 I$, or n_y times the average column driver current, $n_y^2 I$. This peak current pulse requirement must be met by the array line scanning drivers and applies to all four possible dot-matrix array driver configurations (ie. common cathode current source, common cathode current sink, common anode current source and common anode current sink). The disadvantage of matrix addressing as compared to direct address is therefore the higher average and pulse current capacity requirements on the driver circuitry. These requirements can act as practical constraints on how large a single LED display panel can be made, as can the electromagnetic interference (EMI) induced by high pulsed currents.

Another potential constraint on the picture element dimensions ($n_x \cdot n_y$) of a single LED display panel is the saturation of the LED luminance. To hold the perceived (ie. time averaged) luminance of a LED display constant while scanning larger and larger array sizes requires that the pulse duty cycle be reduced to accommodate the larger number of rows or columns to be scanned during the established display refresh time period and that simultaneously the LED instantaneous pulse current be increased so as to maintain the same average drive current and hence luminance. Eventually this process results in increasing the LED current density to the point where luminance saturation occurs. Further array size increases can then be gained only with a reduction in the average luminance the display is capable of producing. This limitation, or variations of it based on voltage saturation, power saturation or simple response time limitations, is shared in varying degrees by all dot-matrix display technologies.

3.5.4.3 Rationale for Modular Display Surfaces

The actual magnitude of the current density induced luminance saturation limit varies with the LED materials used, the techniques used to fabricate the LED junctions and the metalization structure/metallurgy employed. Red emitting LEDs in general have lower pulsed current density saturation limits than do green GaP LEDs, however neither would be adequate for use in fabricating single panel 875 or 1024 line high luminance video displays, for instance. To avoid the ultimate size limitation on sequentially scanned matrix addressed displays, the objective of LED display development has been the development of mosaic displays that use independently refreshed display modules to limit to a small manageable quantity the number of pixels that have to be sequentially addressed using the line-at-a-time address technique. Using this approach, drive current and saturation problems have been successfully avoided for pulse duty cycles of as low as 0.5% or 200 sequentially addressed LEDs per module. It should be noted that in general driver circuit capacity problems are encountered before saturation limits are reached.

3.5.4.4 LED Drivers

The low voltage drive requirements of LEDs can usually be satisfied using commercially available silicon transistors and/or integrated circuits selected to meet the necessary military specification. The choice between common anode and common cathode drive circuit configurations is usually based on the electrical lead current handling capacity of the LED array design employed, which in turn is based on minimising LED junction obstructions due to wires or surface metalisation layers. The common terminal driver, whether it is associated with the common cathode or the common anode configuration, is the one which is scanned and which must handle the high instantaneous current loads. Its primary function is that a switch having a virtually constant saturation voltage independent of whether it is passing the current of one or all of the LEDs in a data addressed row or column.

Whether the inputs to the data line drivers are provided by serial shift registers or by parallel multiplex circuits, the LED address circuitry used with the driver generally must be able to store/latch the transient input data until new data is entered. The essential feature of the data driver is that it functions as a current control circuit. Enabling this circuit using a pulse duration control signal fed simultaneously to all data drivers has provided one straightforward method of controlling the overall luminance of the display under either automatic or manual operator control without influencing the relative luminances of the data displayed. Circuit designs for use with LED displays are still evolving, particularly for video drivers where digital grey shade storage and control are necessary.

For applications such as the graphic display module shown in Figure 3.5.1, it was found necessary to have custom made silicon integrated circuits built in order to make the combined row and column address/driver circuits small enough for mounting on the sides of the module. The advantage of this construction approach is the reduction in driver line power losses, due to the shorter lead lengths, and the reduction in external module connections (i.e. reduced from 128 to 16 parallel data lines/module plus power, ground, clock, control and status sensing for the graphics display module).

3.5.5. SYSTEM INTERFACE

The low signal level requirements present at the input to LED display address lines make these displays compatible with virtually all available types of logic, multiplex and memory interface circuitry. The type and complexity of the LED display system interface is therefore determined almost exclusively by the intended display application and in particular by the complexity and rate of change desired in the information to be displayed, not the display technology to be employed.

3.5.6. VISUAL CHARACTERISTICS

3.5.6.1 Optical Properties

The legibility and efficiency achievable with a LED display depends rather critically on the effectiveness of the optical design which is implemented. In general the design of a LED display should treat the LED material, the substrate to which it is affixed, visible electrical connections to it, any optical coatings applied to the display surfaces and the optical filter or cover glass employed as integral parts of a single composite optical system design. Typical LED processing results in LED wafers and dice having flat smooth specularly reflecting surfaces of between 30 and 38% spectral reflectance prior to encapsulation and 18 to 23% afterwards. The diffuse reflectance associated with the LEDs varies from much less than 1% for vapor phase epitaxial devices up to 2% for some liquid phase epitaxial devices.

The objective of optical filtering any type of head down display is to reduce the maximum combined display reflectance to less than approximately 0.5% or a reflected background luminance of approximately 171 cd m^{-2} . The concept behind this guideline is that head-down displays having sufficient emitted luminance to be legible against the 171 cd m^{-2} background luminance should also be adequate in the glare induced veiling luminance environment created when the sun is within the pilot's instantaneous field of view.

A variety of optical designs capable of satisfying the foregoing requirements have been developed for LEDs. The most cost effective of these designs utilise colour transmission selective filters. Since the inherent diffuse reflectance of the LED is low, the primary objective of the filters is to maximise the filter transmittance to the LED light while

significantly reducing specular reflectance and making a slight reduction in the diffuse component. A filter developed for use with green GaP LEDs, and which meets military specification environmental requirements, may be used as an example of a filter requiring little in the way of special display surface treatment. The filter utilises a laminated sandwich structure consisting of an antireflection coated UV attenuating filter, a neutral density circular polarizer, and an IR absorbing filter with an EMI attenuating antireflection coated rear surface. The circular polarizer effectively attenuates the LED specular reflectance component, the colour and neutral density filtering attenuate the diffuse component and the antireflection coatings minimise the external filter surface Fresnel reflections. A combined reflectance of 0.30% has been achieved using this filtering method. Such techniques are expected to permit the display of up to 8 shades of 'grey'. While the foregoing approach accomplishes the filtering objective, it also restricts the display emitted luminance to between 27 and 35% of that emitted by the LED. As a result more efficient filtering techniques have been developed which concentrate on improving the display surface optical design. One method is essentially equivalent to the black matrix shadow mask approach used on colour CRTs. The most promising approach, based on experimental results obtained to date, involves the application of refractive index matching antireflection coatings to the LED arrays. Combined reflectances of well below 0.5% are expected, while eliminating the need for the circular polariser which at best transmits only about 41% of the LED emitted light.

3.5.6.2 Luminance/Contrast

The present performance of green 25 pixel/cm GaP LED arrays operated at a 1 mA/LED time averaged drive current (ie. 64 mA, 31.25 μ s duration pulses every 2 ms) is 7.54×10^3 cd m⁻² (2,200fL) of luminance spatially averaged over a 200 μ m diameter LED measurement area (ie. 15.4×10^3 cd m⁻² for laboratory devices). When this luminance is area averaged over the surface of a dot-matrix display character, symbol, or image so as to include both emitting and non-emitting areas (ie. assuming no emission between LEDs) an area averaged luminance of 1.5×10^3 cd m⁻² (440fL) is obtained. Roughly equivalent performance can be achieved with red LEDs, which, while more efficient radiometrically, lose this advantage due to the characteristics of the eye.

Contrast ratios achievable using head-down LED displays vary depending on the filtering techniques employed. A low altitude (green LED numeric readout) radar altimeter in the F-111/FB-111 and EF-111 series aircraft produces an area averaged emitted to reflected luminance contrast ratio of one (or an emitted plus reflected divided by reflected luminance contrast of two) in a 100×10^3 Lux (10,000 fc) illuminance environment. A green 7.8x2.6 cm active area 25 pixel/cm resolution LED alphanumeric readout dot-matrix display being produced for evaluation for a potential F-16 data entry display application has been characterised as having an area averaged emitted to reflected luminance contrast ratio of between two and three.

The LED antireflection/refractive index matching filter techniques are planned for use with video, multi-colour and advanced versions of numeric, alphanumeric and graphic displays; this technique should permit eight grey shade legibility on LED video displays.

Radiant intensity spectra of a red LED standby sight plotted as a function of heat-sink temperature are shown in Figure 3.5.5. The intensities are measured in radiometric units and show that as the temperature increases, the peak intensity decreases and moves to longer wavelengths. The effect on perceived brightness is even more pronounced since the eye's sensitivity drops rapidly with wavelength in this region from 72.8 lm W^{-1} at 650 nm to 11.6 lm W^{-1} at 680 nm.

3.5.6.3 Image Quality

Like other dot-matrix display techniques, the LED display exhibits excellent image edge definition. Special design eliminates visible indications of electrical crosstalk. Optical crosstalk between "on" and "off" elements is most severe in monolithic flip chip GaP LED arrays where the material is nearly transparent to the light it generates and no physical boundaries exist between adjacent LEDs. Even in this type of array the luminance measured at an "off" LED immediately adjacent to an "on" LED is typically less than 2.5% of the "on" LED luminance. A greater than 5% optical crosstalk level is capable of producing a visually noticeable effect for a display adjusted to provide a peak image contrast ratio of ten to one. Increasing the contrast by either increasing luminance or reducing the ambient will of course eventually make the crosstalk noticeable.

Dot-matrix displays of all types exhibit spatial variations in pixel luminance and potentially also in pixel colour. These variations can stem both from variations in the drivers used to apply signals to the pixels and from the differences in the electro-optical characteristics of the individual pixels. LED displays having normalised standard deviations in luminance of 12% of the mean value or less have been found to provide satisfactory graphics display image luminance uniformity provided that the luminance variations are spatially randomised across the display surface. By comparison, variations perceptible as row or column luminance variations can, at the same variation magnitude, be obtrusive due to the larger size of the line image.

Luminance variations permissible on displays intended for aircraft video applications are determined by the need to avoid overlap between adjacent grey shades rather than just the issue of whether the variations are noticeable. Using the overlap criteria, a maximum variation of up to 17.2% from the mean grey shade operating level would be permissible for an eight grey shade, $\sqrt{2}$ grey scale ratio video display. Luminance uniformity distributions having a normalised standard deviation of between 8 and 10% from the mean would therefore be capable of satisfying this video LED display luminance uniformity criterion, which can be achieved using developed 50 pixel/cm monolithic chips. However, further processing improvements are desirable to achieve higher chip yields. In general LED arrays fabricated at any resolution using vapor phase epitaxial techniques result in lower luminance variations than when liquid phase epitaxy is used.

Colour uniformity variations either due to process control constraints or temperature variation have proved insignificant for green or red LED's.

3.5.6.4 Flicker/Dynamic Visual Effects

Current production, prototype and developmental aircraft cockpit LED displays employ 500 Hz or higher refresh rate in order to avoid both static and dynamic display image flicker effects. Flicker associated with display imagery which is static or nearly static on an observer's retina may be overcome at a refresh rate of between 50 and 60 Hz, the higher rates being required for larger LED displays. Dynamic flicker or more accurately the appearance of multiple spatially separated images occurs at these low refresh rates as a result of motion of the display image on the retina of the observer's eye. The effect is observed under vibration and also when the observer averts his eyes to look at display information located elsewhere within the cockpit. This dynamic image phenomenon is experienced for all periodically refreshed display media having image persistence durations less than the refresh period (ie. P-43 phosphor CRTs, plasma panels, TFEL and LED are examples). The effect is emphasised in dot-matrix displays due to the sharpness of the imagery portrayed. Refresh rates of 450 Hertz and greater effectively eliminate the phenomenon under practical aircraft cockpit illumination conditions (3.5.6).

3.5.6.5 High Resolution Graphics/Video

LED arrays with resolutions of up to 50 pixels/cm have been successfully demonstrated in both green and red monolithic chips (green in sizes of up to 2.6x2.6 cm). Military specification qualified devices being applied as film annotation arrays in airborne reconnaissance cameras utilise resolutions of up to 46 pixels/cm. A number of arrays at resolution between 40 and 50 pixels/cm have been applied to HUD and HMD displays and to date have been found to provide satisfactory performance when displaying alphanumeric and graphic symbology.

Head-down displays suitable for eight grey shade (ie. $\sqrt{2}$ grey scale ratio) video information portrayal are under development. A grey scale capability was demonstrated by the Japanese in a low resolution display in 1969; recently it has also been demonstrated on a 50 pixel/cm high resolution display surface. See also Section 3.5.7.7.

The very high resolutions being sought for use in HMD video image sources (ie. 200 pixels/cm or greater) have not been attempted using LEDs. Diode junction formation at these resolutions would be feasible; however, a significant advancement in present LED electrical connection fabrication processing techniques would be required to achieve reliable devices. Purer LED substrates would probably also be required to avoid problems in achieving adequate luminance uniformity. No research to develop very high resolution displays has been reported.

3.5.6.6 Colour

Very little colour LED research has been conducted. Red, orange, yellow and green single colour LEDs, due to their importance in consumer and commercial products, have received the greatest research and development emphasis. However, this has been restricted largely to improvements in existing products. Blue and dark green emission colours, which have been demonstrated in large energy gap materials such as gallium nitride and silicon carbide, have been virtually ignored from a research and development standpoint. Difficult processing, very low initial emission efficiencies, and a generally conceded low prospect for high volume device sales in green and blue displays has been responsible for this situation. Metal-insulator-semiconductor LEDs have fared little better, an exception being the dark green emission zinc telluride devices.

Lacking an efficient material capable of producing blue, and therefore potentially also green and red, a full colour LED display is at best a possibility for the distant future. Gallium phosphide which has served as the basis for efficient green, yellow, orange and red single colour LEDs has been the subject of very modest government funded multi-colour LED display research (3.5.7). Two terminal multi-colour hybrid and monolithic LEDs utilising current density to control the mixing of the red and green primary emission colours and using pulse duration to control luminance have been demonstrated. Attempts to achieve spatially uniform mixed colour that would be satisfactory for application to large area multi-colour displays proved to be beyond the means of the modest development efforts conducted.

More recent multi-colour display research has concentrated on monolithic LED arrays utilising independent red and green primary colour diode junctions (to provide yellow and orange mixed colours) in a superimposed geometric structure. This structure is suitable for low resolution displays because the colour mixing occurs within the LED. The technique has also provided LED efficiencies approximately the same as those of single colour red and green LEDs. Colour dot resolutions of 16, 25 and 50 colour dots/cm have been demonstrated, the latter is up to 12.6 cm square monolithic chips. Improvements in colour uniformity and demonstration in the four-edge abutable 2.6 cm square modular

building block format, needed for large area head down displays, still must be accomplished to prove the feasibility of this multi-colour display approach.

3.5.6.7 Viewing Angle

The viewing angle associated with LED displays depends on the optics used to form the final display product. The use of restricted viewing angle lensed LED indicators and displays is common in consumer product applications where it is assumed that legibility will be achieved by orienting the display. In head-down aircraft display applications the displays are attached to instrument panels at locations which can result in viewing angles of up to about 45° . The latter application is satisfied using flat LED arrays. These arrays may be viewed at angles approaching 90° from a normal to the display surface. This is possible because the luminance of the characters depicted using these LED arrays remains approximately constant as a function of viewing angle, although the apparent foreshortening of display characters experienced at large viewing angles (ie. $>60^\circ$) should be avoided.

3.5.7. STATE OF DEVELOPMENT

3.5.7.1 Head-Up Displays (HUD)

It has become conventional to construct head-up displays with standby sights, optically mixed into the collimation system, which may be used if the cathode ray tube or its drive circuits fail. It is advantageous for the purpose of optical combination for the standby reticle to be of a different colour to the green cathode ray tube and they have conventionally been implemented in red. Since red LED's are particularly efficient and crisp definition is required, a fixed-format light emitting diode device is very suitable and has been successfully evaluated in flight. A device for a typical standby sight is shown in Figure 3.5.3, before the processed slice has been cut into individual devices, and consists of a central 'pipper' diode 0.17 mm in diameter surrounded by a separately addressable segmented circle 1.7 mm in diameter. It can be seen that the aluminium metalisation has been defined as grids over the diode areas to spread the current and give uniform luminescence.

The luminance of the two types of diode as a function of current density at 20°C is shown in Figure 3.5.4. The required maximum luminance for standby sights is approximately $30 \times 10^3 \text{ cd m}^{-2}$, which can be achieved with current densities below 1 A mm^{-2} . In fact brightnesses much in excess of this figure are achievable with the 'pipper' diode, since its small area involves currents of less than 50 mA. The same is not true for the outer-circle diodes. With an area of just below 1 mm^2 currents of the order of 1 A are required to achieve the specified luminance. Even with massive heatsinking, the thermal impedance of the GaAs results in a significant junction temperature rise which causes the luminance to saturate, as shown in Figure 3.5.4.

Life-test results of the outer diode areas, driven at current density of 0.80 A mm^{-2} , corresponding to an initial 20°C brightness in excess of $35 \times 10^3 \text{ cd m}^{-2}$, are summarised in Figure 3.5.6. Even at 125°C times to half brightness in excess of 10^4 hours are obtained.

These results demonstrate that LED devices are ideally suited to standby-sight applications, provided that the format is designed to minimise individual junction areas. The total size possible for a single monolithic device is determined by the size and shape of the starting epitaxial wafer and by the internal diameter of the diffusion capsule. The largest standby sight produced to date measures $20 \times 15 \text{ mm}$ and contains 36 separately addressable areas.

3.5.7.2 Helmet-Mounted Displays (HMD)

Whereas helmet mounted sights have found applications in target designation and weapon aiming it is highly desirable to make provision for information display which include target information, threat warning, weapon status and/or provision for cueing a pilot onto a target detected by another sensor (eg. a radar). In such a display, the optical solution adopted is shown schematically in Figure 3.5.7. Light from the display is collimated at the eye by curved surfaces on the exit face of the prism and at the combiner on the helmet visor. Since the wavelength of the light is close to the limit of the eye's sensitivity, a dichroic coating can be used which has a high reflectivity for the LED without producing noticeable colouration of the outside scene.

A monolithic common-cathode display intended as a threat-warning indicator in helmet-mounted systems is shown in Figure 3.5.8. This display, measuring 5x5 mm, contains 65 individually addressable diodes. Many other formats of the same complexity are possible. The limiting factors in the design of such devices is the need to bring the conductor tracks to the outside of the chip and the comparatively large size of the bonding pads.

Such monolithic arrays have restricted formats, chosen at the design stage, which can be used for dedicated tasks only, such as sighting or threat warning. Matrix addressable displays, on the other hand, would be capable of performing a variety of functions and thus give greater flexibility to the design of avionic systems. The matrix displays need to have a resolution of at least 4 lines mm^{-1} and to be capable of achieving a mean brightness of approximately $15 \times 10^3 \text{ cd m}^{-2}$.

A fabrication technique which uses standard commercial material is illustrated schematically in Figure 3.5.9. The $\text{GaAs}_{0.6}\text{P}_{0.4}$ slice is processed as for the common-cathode displays with a diode matrix being produced. Each p-type area has an individual contact pad delineated on it and the entire n-type back surface has a single ohmic contact applied over it. After cutting it to size the device is bonded to a metallised ceramic substrate, and air isolating channels are formed between the diode columns. These channels penetrate the ceramic substrate through the metallised layer to align the device automatically for subsequent packaging. The rows in the matrix are then formed by conventional stitch bonding techniques to join up appropriate p-contact pads.

This technique has proved satisfactory for producing small arrays for helmets, and a packaged 32x32 array, with 4 lines mm^{-1} resolution has been supplied in quantity.

In the absence of suitable integrated drivers the array is driven by discrete transistor stages. The array and bond wires are protected from damage by an anti-reflection-coated corundum ($\alpha\text{-Al}_2\text{O}_3$) window.

Future developments include both improving the efficiency of the LEDs by optimising the material preparation, and increasing the resolution to the level at which HMDs may become a primary display surface for avionic systems. Another important development is that of integrated logic/drivers capable of handling the peak currents required. This will enable the display and electronics to be mounted on the same package to increase reliability, and more importantly lead to a decrease in weight on the pilot's helmet.

A helmet-mounted display with a matrix-addressed reticle (20x23 addressable points) was first evaluated by the Naval Air Test Centre, for energy management and aircraft limit indication to a combat pilot. A series of trials (Ref.3.5.8) has provided full validation of the concepts explored. A brief trial was also carried out under the sponsorship of the UK Ministry of Defence of the use of a similar display in helicopters

for head up indication of principle navigation parameters and has been favourably reported on. Assessments by British Aerospace and the Royal Aircraft Establishment of matrix-addressed helmet displays in fixed simulators, in moving base simulators reproducing flight vibration, and in actual flight, continue as this report is being compiled. A version suitable for flight and completely integrated with the UK Mk IV helmet has been developed, undergone blast tests appropriate to ejection and is under evaluation.

3.5.7.3 Head-Down Numeric Displays

A photograph of an operating low altitude radar altimeter developed and produced for use in all F-111/FB-111/EF-111 series aircraft is shown in Figure 3.5.10. The instrument is believed to represent the first installation of an instrument incorporating a LED display in an operational military bubble canopy type aircraft. The altimeter uses four 7.1 mm high green LED readouts to provide the pilot with precise altitude information. The digitally driven round-dial indicator provides altitude trend information and a red LED provides a low-altitude warning indication. The unit also includes an illuminance sensor, located adjacent to the numeric readout and warning indicator displays, which is used to automatically control the luminance of these displays over their entire operating range. A manual brightness control allows the pilot to adjust the LED displays to a comfortable level for night viewing.

During flight tests by Strategic Air Command and Tactical Air Command aircrews, the pilots rated the legibility of the LED readouts as being very good and the instrument overall as a significant improvement over existing conventional indicators. The overall reliability of the instrument for any single component failure was specified at 10,000 hours mean time before failure and the instrument was provided to the USAF with a 5000 operational hour (as indicated by a rear panel elapsed time indicator) repair or replacement warranty.

A variety of different LED numeric displays applied to applications such as clocks, status readouts, etc, are currently in use in the less severe illumination environments found in commercial and private aircraft. Similar applications of LED numeric displays within conventional electromechanical instruments have been developed by Smiths Industries and Plessey for use in military aircraft such as the British Aerospace Hawk.

3.5.7.4 Head-Down Programmable Pushbutton Switch/Keyboards

An operating programmable pushbutton utilises a 35x16 pixel array of green gallium phosphide high efficiency LEDs at a resolution of 16 pixels/cm and has an active area of 2.2x1 cm. The array is designed to permit the display of two rows of up to six character font or a lesser number of vertically centered larger font characters. The switches contain their own individual drive and address electronics and can be used either individually or can be four edge abutted to form a multi-function programmable keyboard of any desired size.

The information portrayal capabilities and methods of interfacing and utilising the switch/keyboard with aircraft systems are being established by Boeing based on the extensive research they have conducted in recent years aimed at developing and refining effective multi-legend interactive display techniques and information portrayal methodologies. The switches, which are being developed to meet full military environmental test conditions, will be available in mid 1983.

An alternative LED programmable pushbutton demonstrator which utilises a single display panel containing both a scratch pad display and a 3x3 matrix of switch displays overlaid

by a clear plastic touch panel has been developed. Each switch area in this display contains two separated rows of four character word, 5x7 dot-matrix font red LEDs. In a newer version currently under construction the switch matrix size is increased, the switch word lengths have been extended to eight characters per word and higher luminance yellow LEDs are used. Both displays have a 20 pixel/cm resolution but neither has as yet been designed to be legible in a bubble canopy aircraft cockpit environment.

3.5.7.5 Head-Down Data Entry Display

The data entry display shown operating in the photograph of Figure 3.5.11 was developed for use as a feasibility demonstrator/simulator test display. The display has a 7.8x2.6 cm active area viewing surface and was constructed by edge abutting three 2.6 cm square nominal 25 pixel/cm resolution green LED graphic display modules (see Figure 3.5.1). The display provides an area averaged contrast ratio (ie. emitted luminance divided by reflected luminance) of in excess of two.

3.5.7.6 Head-Down Vector Graphics Displays

Two advanced development model versions of a 25 pixel/cm resolution green LED graphics display are currently nearing completion. The photograph of the first display was shown in Figure 3.5.2 and its visual characteristics have been previously described. This 320x256 pixel (13x10.4 cm) display system was designed for use in an extensive flight simulator evaluation test program to be conducted by the U.S. Air Force Flight Dynamics Laboratory. The purpose of the testing is to assess pilot performance/acceptance of the 25 pixel/cm dot-matrix graphic information presentation technique and to establish display information format restrictions, if any, that would be necessary when applying the display to airborne flight control and avionic data monitoring piloting tasks. The display system is designed to accept avionic input data rates of up to 50 Hertz and, through display system data processing, provide interpolated/extrapolated imagery at selected frame rates of up to 250 Hertz (ie. a constant 500 Hertz refresh rate is used). The display is programmed to portray formats utilising from low to medium speed imagery for the purpose of initial testing (ie. an electronic attitude director indicator (EADI), an electronic horizontal situation display (EHSI), a navigation-vectoring display (NI), a precision approach indicator display (PAI) and an engine status indicator (EAI) in two formats). Later phases of the program are to assess advanced display formats and high display surface image speed information portrayals.

The second graphics display is a flightworthy version which has a 13 cm square nominal 25 pixel/cm resolution display surface made up of 25 of the previously described green LED modules.

3.5.7.7 Head-Down Video Displays

Nearing completion is a nominally 50 pixel/cm 2.6 cm square, grey shade (ie. 2 grey scale ratio) video demonstrator display that is being developed under the joint sponsorship of the Canadian Department of Industry, Trade and Commerce and the U.S. Air Force Flight Dynamics Laboratory. A photograph illustrating the grey shade rendition capability of a preliminary green LED array, developed to assess both the breadboard drive/address electronics and the 128x128 element solid state image plane video camera to be used with the final deliverable LED array, is shown in Figure 3.5.12. The demonstrator display was restricted to the size of a single four-edge abutable module (128x128 pixels at about 50 pixels/cm resolution) to conserve resources. Since the electro-optical performance demonstrated by a single module gives a direct measure of the performance to be expected from fully populated 525, 625, 875 or 1023 line video

displays, formed as a mosaic of modules, the restricted area demonstration is still quite meaningful. Array alignment, grey scale rendition, luminance uniformity, colour uniformity, luminance control, optical and electrical coupling, and module edge abutment potential were the primary development criteria for this display. Luminance output and display reflectance were secondary development issues; however, measurements on sample arrays under the video drive conditions have yielded $1.4 \times 10^3 \text{ cd m}^{-2}$ outputs. The sample arrays did not incorporate the refractive index matching film techniques previously described.

Results obtained to date indicate that single colour video LED displays suitable for use in bubble canopy aircraft cockpits are feasible. The feasibility of video multi-colour displays utilising the demonstrated 50 dots per cm colour LED arrays cannot yet be assessed since necessary research into monolithic chip electrical interconnection techniques compatible with four-edge abutable colour module construction has not been conducted.

3.5.8 Acknowledgements

The authors wish to acknowledge the contributions of Dr D. Wickenden of the General Electric Company p.l.c. (UK), Mr D. Kennedy of Optotek Canada. Part of the UK aspect of this work has been carried out with the support of the United Kingdom Ministry of Defence and part of the United States aspect with the support of the Flight Dynamics Laboratory, US Air Force.

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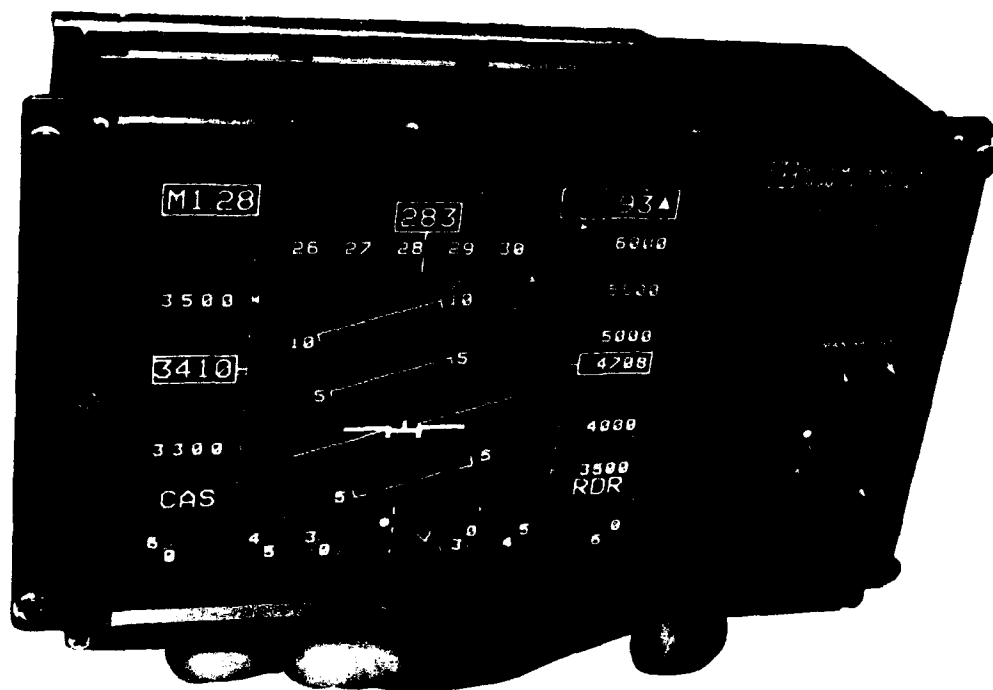


Fig.3.5.1 Green emitting 64 x 64 pixel 2.6 cm square
4-edge abutable led display module

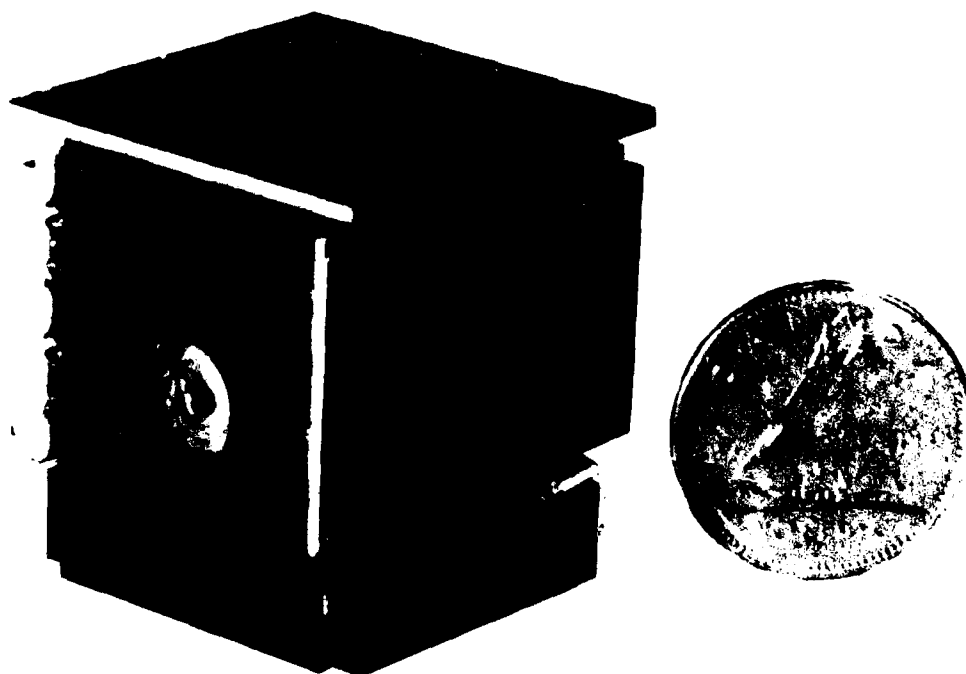


Fig.3.5.2 Photograph of an operating high speed graphics
display with a 20 module mosaic surface

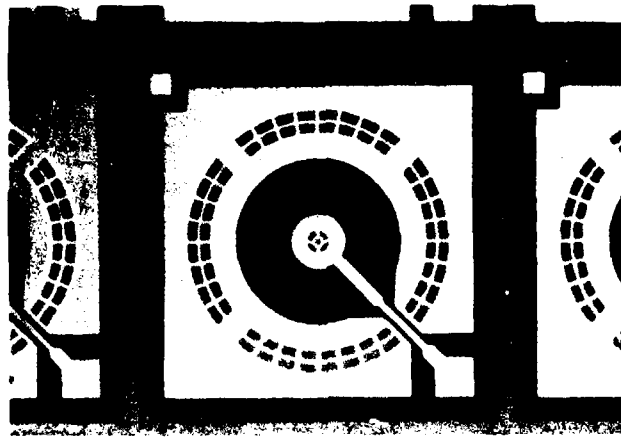


Fig.3.5.3 A typical head-up display standby-sight

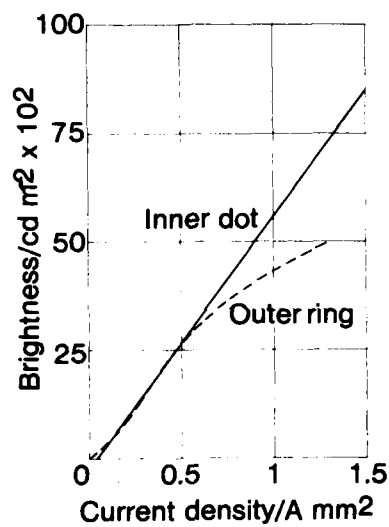


Fig.3.5.4 Brightness of red emitting standby-sight leds as a function of current density

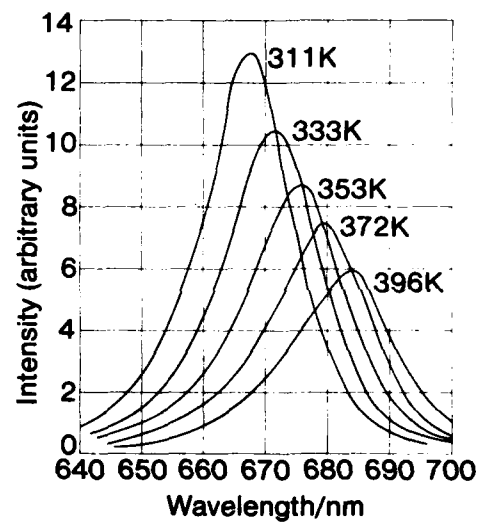
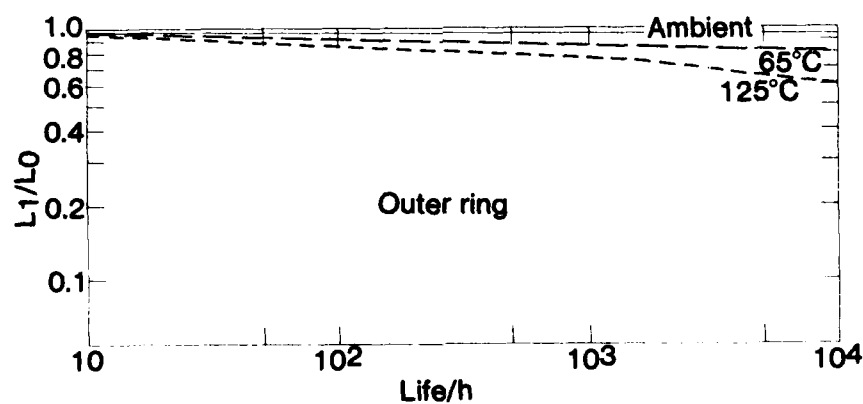


Fig.3.5.5 Radiant intensity spectrum of red emitting leds as a function of heat sink temperature

Fig.3.5.6 Standby-sight life test results: $i=0.66$ A, $j=0.815$ A/mm²

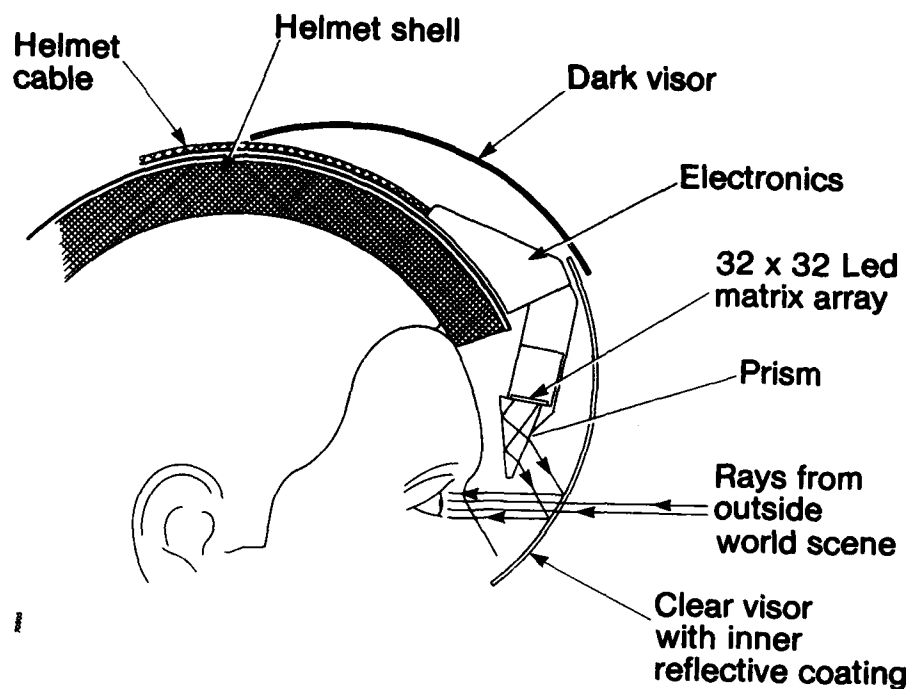


Fig.3.5.7 Cross section of the helmet mounted display



Fig.3.5.8 Helmet mounted threat-warning indicator

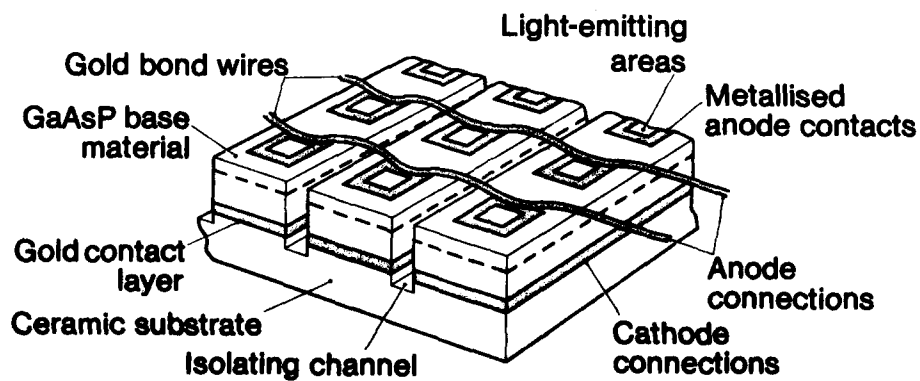


Fig.3.5.9 Method of fabrication of a monolithic led matrix



Fig.3.5.10 Photograph of an operating f-111 green led numeric readout low altitude radar altimeter



Fig.3.5.11 Photograph of an operating green led data entry display with a three module mosaic surface



Fig.3.5.12 Photographs of an operating 2.6 cm square 128 x 128 pixel breadboard video display surface (full scale)

LIQUID CRYSTAL DISPLAYS
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SUMMARY

Although liquid crystalline materials have been recognized for over 100 years, their potential in display devices has become apparent only during the last 15 years. In this time many different effects have been discovered and assessed in laboratories, commercial exploitation has been rapid and extensive, and a few displays have already been fully developed for military use.

This lecture will introduce the physical properties of liquid crystal materials and describe a selection of the more significant effects exploited in displays, pointing out their relative advantages and limitations. The present "state-of-the-art" will be summarized and some tentative predictions for future performance will be made.

1 INTRODUCTION

The term "Liquid Crystals" was first used by Lehmann in 1890, and is applied to substances which flow in the manner of normal liquids, but whose optical behaviour is similar to that of crystals. It designates a state of matter, intermediate between solids and liquids, having some of the properties of both. Liquid crystal phases are called "mesophases" because of this intermediate nature.

Commercial developments of Liquid Crystal Displays (LCDs) have concentrated on numeric and small alpha-numeric displays, and have largely replaced LEDs in applications such as digital watches and calculators. The attractive features of LCDs are:-

- a) the display does not emit light, it merely modulates the ambient light and retains good appearance in even the brightest conditions. Low power subsidiary illumination is readily provided for night-time viewing;
- b) display power consumption is minimal, a few microwatts per square centimetre, so continuous battery-powered operation is feasible over long periods;
- c) displays operate at low voltages, from 2 to 20V, compatible with low power integrated circuit drivers;
- d) lifetimes in normal environments can be very long, up to 50,000 hours or more;
- e) manufacturing costs in large quantity production are very competitive;
- f) displays may either be viewed directly in reflection or may be projected onto large screens.

There are disadvantages as well:-

- a) the liquid crystal phase only exists over a limited temperature range, typically 100°C around room temperature, so it is difficult to meet the full operating range of military equipment, -55°C to +85°C, without subsidiary heating;
- b) at low temperatures the display response is slow;
- c) the most frequently used display effect, the "Twisted Nematic" effect, requires polarisers which limit the display brightness;
- d) the twisted nematic effect may only be matrix addressed with a limited number of lines. Complex displays in many cases require active element addressing circuitry, eg MOSFET or Varistor, for each display element.

The aims of this article are to provide a background understanding of liquid crystals, the effects used in displays and their limitations; to summarise the capabilities of the present generation of production displays; to describe a selection of experimental prototypes potentially capable of extending the range of application of LCDs. Section 2 deals with a range of background information on liquid crystals relevant to display applications, followed in Section 3 by a description of the principle optical effects used in displays and the performance of simple, directly driven, displays. Section 4 discusses the difficulties of matrix addressing LCDs and deals with a number of approaches aimed at overcoming the problems.

2 BACKGROUND INFORMATION

Detailed references are not given in this section; for more comprehensive reviews and bibliography, see references (1) to (3).

Liquid crystals are generally composed of long thin organic molecules, the distinguishing feature of the liquid crystalline state being the way in which the molecules are spatially arranged. In a perfect crystalline solid the relative positions and orientations of the molecules are well defined, whereas in a liquid the relative positions and orientations are virtually random. In a liquid crystal, however, the relative orientation of the molecules remains well defined, but various aspects of the positional ordering of the crystal are lost, as shown in Figure 1. In a "nematic" liquid crystal all positional order is lost, only the orientational order remaining. In a "smectic" material, of which there are several types, the molecules are constrained in layers but are randomly positioned within the layers. "Cholesteric" materials are closely related to nematics, but have a small angular twist between molecules which results in a spiral structure of well defined pitch. In spite of all this ordering, however, liquid crystals are clearly liquid, flowing readily with quite low viscosity. Consequently the orientational order of the molecules is not preserved automatically over indefinite distances as in a solid crystal, but exists typically over distances up to perhaps a millimetre.

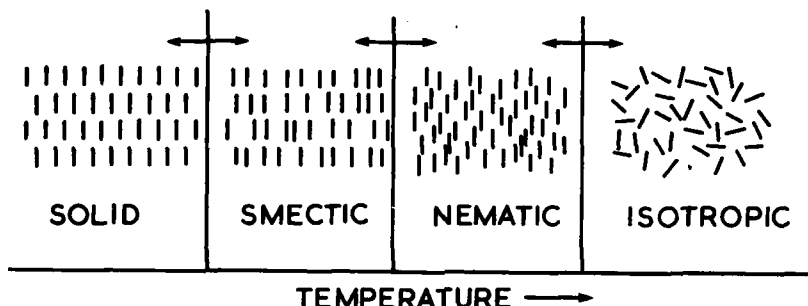


Figure 1. Phase diagram and schematic structure of a hypothetical liquid crystal.

Figure 1 illustrates the phase diagram of a hypothetical liquid crystal, showing one nematic and one smectic phase. In real materials the number of distinct smectic phases may be different, and the nematic phase may be absent or replaced by a cholesteric phase. In this diagram no attempt has been made to represent the thermal fluctuations (Brownian motion) which disturb the ideal alignment shown here to an extent which depends on the sample temperature.

An important concept is that of the "director" which describes the local alignment direction of the molecules. It does not refer to the orientation of an individual molecule, since that is subject to thermal fluctuations, but rather it refers to the average orientation of a group of molecules.

A most significant aspect of liquid crystals is the large anisotropy of most of their physical properties when measured in directions parallel and perpendicular to the director. For example, the anisotropy of dielectric constant means that electric fields can be used to control the orientation of the director. This effect is utilised in all the displays discussed later. This dielectric anisotropy may be either "positive" (ie maximum dielectric constant parallel to the director) or "negative", and both types of material have been exploited in displays. The anisotropy of magnetic susceptibility is also significant and permits orientation control by magnetic fields. This is used extensively in research but has not yet been exploited for display purposes. The anisotropy of refractive index, usually between 0.1 and 0.2, is much greater than in most crystalline solids and is the basis of most optical effects used in displays. Other physical properties, such as electrical conductivity, elasticity, viscosity, etc, are also strongly anisotropic and have significant effects on the static and dynamic behaviour of materials and devices.

Finally, liquid crystal materials may also interact strongly with solid surfaces. These effects are also important since, in the absence of electric or magnetic fields, the structure and orientation of thin layers of liquid crystal are largely determined by surface interactions. Methods have been developed of treating glass surfaces with organic or inorganic films, possibly followed by controlled mechanical abrasion, which align the director either perpendicular to the surface ("homeotropic" alignment), or parallel to the surface ("homogeneous" or "planar" alignment) or at some intermediate angle. This control of alignment via surface forces permits very large areas of uniform orientation and texture to be produced, which is also important for the uniform appearance of displays.

Several distinct electro-optical effects have been demonstrated in liquid crystals for display purposes. These include various scattering effects, interactions with polarised light to produce either variable colour or monochrome contrast, birefringence, absorption in dissolved dyes, etc. All of these effects involve molecular re-alignment caused by the interaction between the applied electric field and the dielectric anisotropy of the liquid crystal. Furthermore, over a wide range of drive conditions it is found that the response of the liquid crystal is determined by the root mean square (RMS) of the applied waveform, rather than by the peak amplitude. Drive waveforms are normally constrained to be AC since, although liquid crystals respond to DC, the presence of DC gives rise to various electrochemical reactions which may rapidly degrade the display.

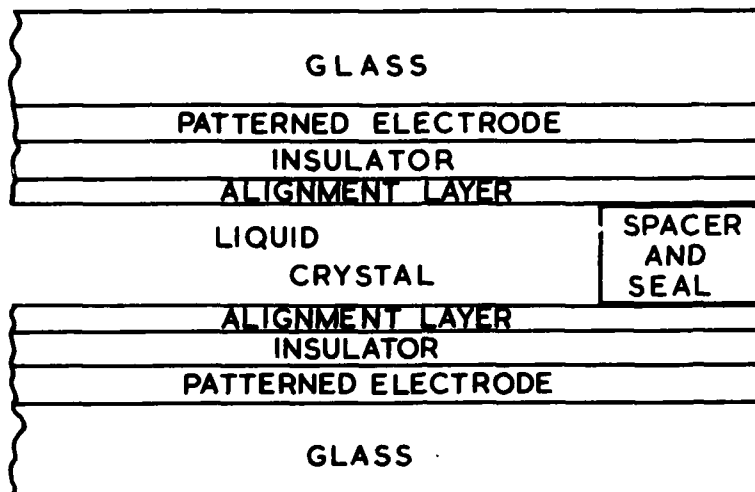


Figure 2. Schematic representation of a typical liquid crystal cell, not drawn to scale.

The construction of a typical liquid crystal cell is shown in Figure 2. The figure, which is not to scale, shows the two flat glass substrates which are separated by a uniform space, typically between 5 μ m and 20 μ m thick, which is filled with the liquid crystal. The inner walls of the glass are covered by the electrode patterns which define the active areas of the display. In transmissive cells both electrode layers are made of a transparent conductor such as an indium tin oxide mixture, whereas in some reflective cells the rear set of electrodes may be metallic. Covering the electrodes are insulator layers of sufficient thickness to protect the liquid crystal from inadvertent exposure to DC. Finally the insulators are coated with the appropriate alignment layers if needed. The spacing of the cell is often controlled by a spacer around the periphery, though rather better spacing control is sometimes obtained using inconspicuous spacers distributed over the whole area. The cell is sealed around the edge by either a thermoplastic bond or a higher temperature, more hermetic, glass-frit technique. The polarisers and reflectors required by some display effects are attached to the outside of the glass.

In order to be generally acceptable there are many requirements placed on the materials. Firstly, it is vital that they should be non-toxic, both for ease of handling during manufacture and to avoid risks caused by breakage during use. Secondly, they should be highly stable, not only to ensure long life in the operating environment, but also to avoid the need for difficult and costly manufacturing processes. Many of the early liquid crystal materials were suspect on account of either toxicity, susceptibility to atmospheric oxidation or to degradation caused by blue or ultraviolet light. The discovery of the biphenyl family (4, 5), however, has provided a satisfactory solution to all of these problems. Indeed, some manufacturers now claim operational lifetimes in excess of 30,000 hours.

Temperature has many effects on LCDs. The most important consideration is the range over which the material remains liquid crystalline. This is bounded of course at high temperatures by the transition to an isotropic liquid, and at low temperatures by a transition either to another liquid crystal phase of higher order or to a solid phase. The nematic to isotropic transition is well-defined, but solidification is often accompanied by extensive super-cooling. It is most important that the quoted minimum temperature for a material represents melting from the solid and does not rely on supercooling: the super-cooled state is only metastable, and damage to the surface alignment layers is possible if repeated solidification occurs.

Single chemical compounds are rarely liquid crystalline over a useably wide temperature range, but multi-component mixtures have been developed (6) which have nematic phases over a wide range. Figure 3 shows the phase diagram of a two-component mixture of biphenyls, where the eutectic composition is nematic from 20°C to 70°C. By adding precisely determined quantities of other materials a multi-component eutectic can be made with even wider range. For example, the four-component mixture E7 (BDH nomenclature) used in watch displays operates from -10°C to +60°C. More recent mixtures have considerably extended this range and at the same time afforded improvements in other material parameters.

Good liquid crystal materials have high resistivity, $> 10^{10} \Omega\text{cm}$, so that cells normally present an impedance of $> 10^7 \Omega$ per square cm in parallel with 1000 to 3000 pF per square cm. When driven with low frequency AC the power dissipation is consequently limited to a few microwatts per square cm.

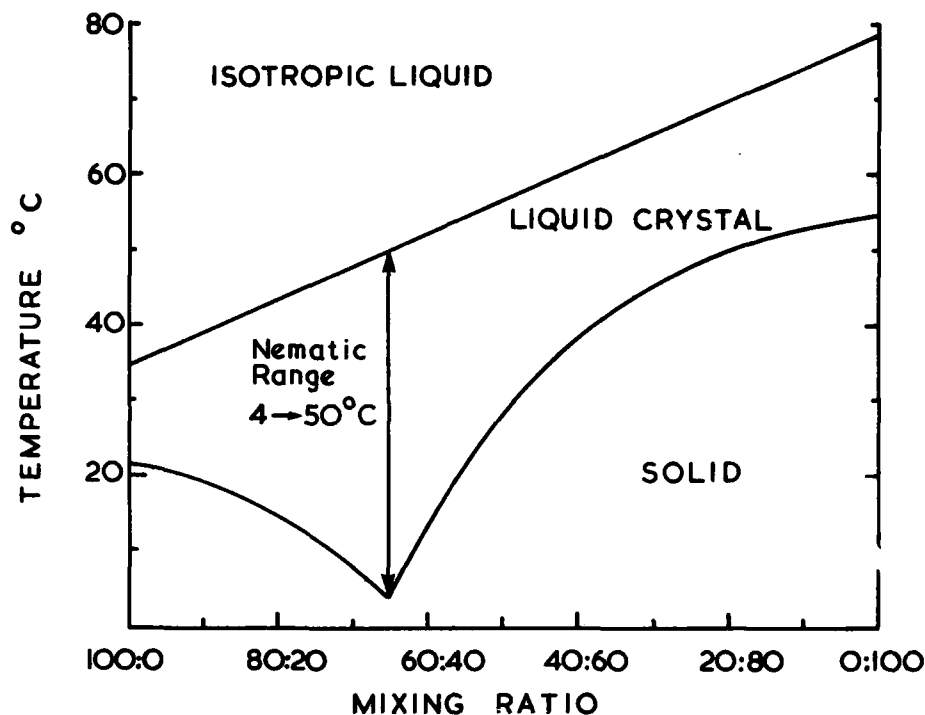


Figure 3. Phase diagram of a two-component liquid crystal mixture, showing the wide temperature range of the nematic phase at the eutectic composition.

3 DISPLAY EFFECTS AND SIMPLE DISPLAYS

3.1 Dynamic Scattering

The dynamic scattering effect (7) was the first LC effect to be used in displays, some 80 years after Reinitzer first observed a liquid crystal phase in 1888.

The effect uses a nematic material of negative dielectric anisotropy containing a dopant to increase its conductivity. Homogeneous alignment layers ensure that clear transmission occurs in the undriven (off) state. An applied electric field produces both current flow and a torque on the molecules. When a critical threshold field is exceeded a turbulent flow condition occurs. In this state the director alignment is lost and spatial variations of refractive index occur on a scale suitable for strong light scattering. The on-state then appears cloudy.

No polarizers are required so the display brightness can be quite high, but contrast depends critically on the illumination conditions and may be poor.

This display effect has never received widespread popularity, though it is occasionally used for special purposes where illumination can be carefully controlled. One other reason for its lack of general acceptance is that the display lifetime tends to be degraded by the ionic additives needed to achieve the appropriate conductivity.

A similar effect is also obtainable in certain smectic materials. This will be mentioned again in Section 3.6.

3.2 The Twisted Nematic Effect

This is the effect used in the vast majority of liquid crystal displays produced over the last 10 years, following the pioneering work of Schadt and Helfrich (8).

A schematic twisted nematic (TN) cell is shown in Figure 4, where a material with positive dielectric anisotropy is used. The diagram of the off-state shows homogeneous alignment on both surfaces of the cell, with these two alignments mutually at right angles. The director then spirals uniformly from one surface to the other giving the 90° twist that is used to name the effect. (In practice various defects in performance are avoided if the surface alignment is not precisely homogeneous, tilt angles of up to 30° from the surface being used in some instances, but this does not materially affect the description given here). The front polariser produces linearly polarised light whose polarisation direction is either parallel or perpendicular to the director at that face. Because of the large refractive index anisotropy of the liquid crystal the plane of polarisation is guided through the cell, following the rotation of the director. It thus emerges polarised orthogonally to the incident polarisation. If the analyser is perpendicular to the polariser this emerging light is transmitted.

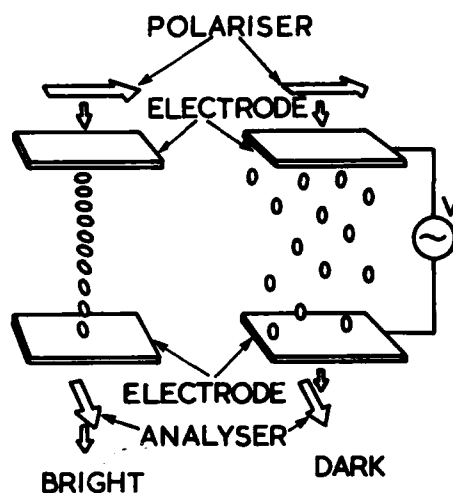


Figure 4. Twisted nematic cells in ON and OFF states, used in transmission between crossed polars.

When a voltage above threshold is applied, the director rotates to be parallel to the electric field in all places. No guiding of polarisation occurs, so the transmitted light is absorbed by the analyser. Of course, by rotating the analyser through 90° the opaque and transmitting states are reversed.

When the applied voltage is reduced below the threshold value the surface forces then re-establish the original twisted structure.

The display may be used either in the transmissive mode with an independent light source illuminating the rear of the display, or it may be used with a suitable reflector stuck to the rear polariser to reflect the ambient light. In the latter case a diffuse reflector which does not depolarise the light is required to maximise the display brightness and contrast.

An elegant, low power, solution to night-viewing of reflective TN displays is to use a "transflective" rear reflector, ie a reflector that transmits say 10% of incident light. A very weak light source, possibly a beta-light, placed behind this transflector then gives good transmissive mode viewing in the dark, with a smooth transition to reflective mode viewing at higher light levels.

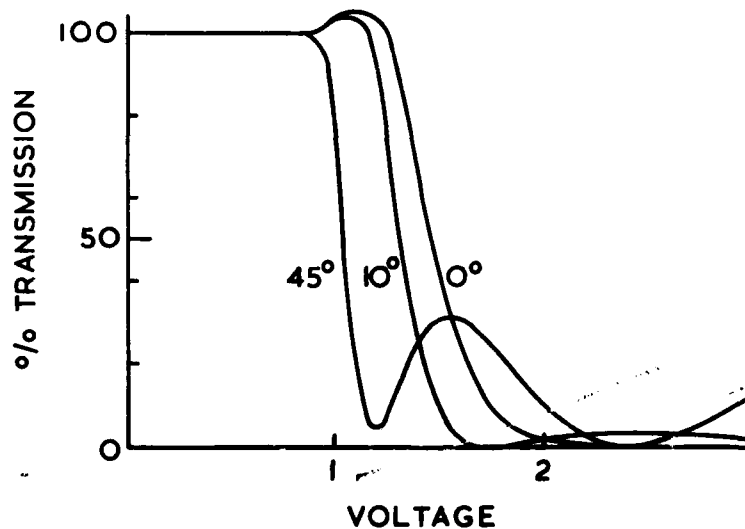


Figure 5. Normalised optical transmission of a TN cell between crossed polars as a function of applied voltage at three angles of incidence. The 10° and 45° data apply to the "low voltage" quadrant.

For low power, portable applications, drive voltage is a most significant consideration. Figure 5 shows the transmission at normal incidence of a TN cell plotted against applied voltage. There is a fairly well defined threshold voltage, V_T , normally occurring between 0.8V and 1.5V. The transmission then falls to $\sim 10\%$ by between 1.3V and 2.2V. To achieve good contrast requires drive at about $2 \times V_T$, although quite usable contrast is obtained at slightly lower voltages. Since power dissipation is roughly proportional to the square of the drive voltage it is clearly beneficial in terms of battery life to operate with low V_T materials. Batteries, however, are available only at certain voltages, so the major consideration may often be to match the required liquid crystal drive voltage to that produced by 2 or 3 cells of a specified battery.

The appearance of a TN cell driven slightly above threshold is a strong function of the direction from which it is viewed. This arises because the molecules are constrained to rotate in a particular direction in going from the off to the on state. The threshold voltage for the optical effect is lower than that at normal incidence in one particular viewing quadrant, known as the "low voltage quadrant". From all other directions the threshold is higher. It is therefore most important to obtain the optimum relative positions of display, observer and illumination. The observer should always view from within the low voltage quadrant. The ambient illumination may throw shadows of the displayed data onto the rear reflector. Usually these shadows increase the observed contrast, but if the reflector is a significant distance behind the liquid crystal layer then there may be disturbing parallax between the data and its shadow. In this case the intensity of the shadows may be reduced by illuminating from directions well outside the low voltage quadrant.

The threshold voltage, V_T , of most liquid crystals is temperature dependent, so the temperature coefficient, dV_T/dT , is a parameter of interest. Typical values range from -0.4 to -1.0% per $^\circ\text{C}$ for TN materials. This effect is not too important for directly driven displays, providing that enough volts are available to turn the display fully on at the lowest temperature, but it is a very significant parameter for multiplexed displays (see Section 4).

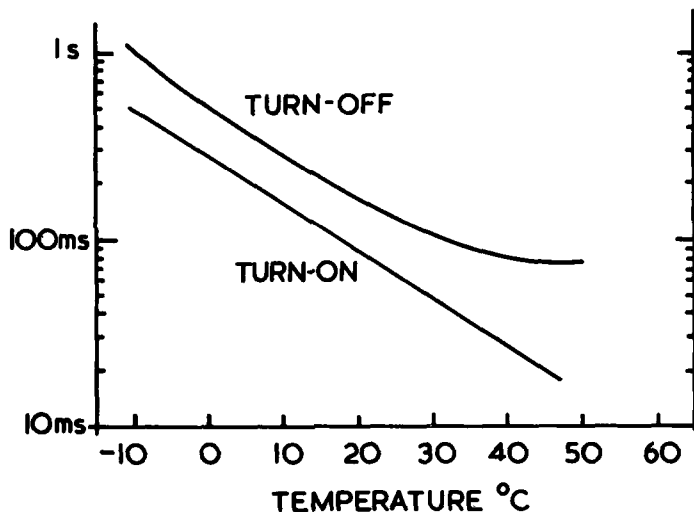


Figure 6. Variation of response times of a typical TN cell with temperature. Cell spacing, $12\mu\text{m}$, material E7. Note that response times are proportional to viscosity and to the square of cell spacing.

Perhaps the most striking effect of temperature is on the response speed of the display. This is determined largely by the viscosity of the material which is almost inevitably a strong function of temperature. Figure 6 shows the variation of both turn-on and turn-off times for a particular TN display as a function of temperature. It is clear that, while rapid response is possible at room temperature and above, response is very sluggish below 0°C . Increasing the drive voltage speeds up the turn-on time, but, since the turn-off driving force is determined by the surface alignment layer, one is able to affect the turn-off speed only by reducing the viscosity. In principle one could achieve faster response with a given material by reducing the cell spacing, but in practice this also affects many other aspects of cell design and cannot be reduced. Materials are continually improving, however, and low temperature viscosity values at least a factor of 4 lower than that of E7 are now available. When used in thin cells the low temperature response time is greatly improved.

There are many other less significant effects of temperature on liquid crystal parameters, for example resistivity, cell capacitance, refractive indices, etc, but no discussion of them will be included here. The remaining effects of temperature relate to the cell. In general two methods of cell sealing are in commercial use. The first uses a low temperature, $\sim 150^\circ\text{C}$, thermoplastic bond. This is perfectly reliable for most domestic applications but there are doubts about its reliability in harsher military environments, particularly in hot, humid situations. The second uses a high temperature, $\sim 500^\circ\text{C}$, glass frit method which produces a fully hermetic bond capable of withstanding much harsher environments. The TN cell, however, faces the added problem that the adhesion of the polarisers is liable to degrade in hot, humid conditions unless some form of secondary encapsulation is used.

3.3 The Cholesteric-Nematic Phase Change Effect

With this effect (9) no polarisers are required, the display being switched electrically between transparent and scattering states. The cell is filled with cholesteric material of positive dielectric anisotropy, the cholesteric pitch being a small multiple of the wavelength of light to optimise the scattering effect. When a field above threshold is applied the positive dielectric anisotropy causes all molecules to align parallel to the field, the cholesteric twist is lost and the molecular ordering and alignment are similar to the on-state of the twisted nematic cell. Since no polarisers are used the cell is completely transparent. When the field is removed the cholesteric twist is rapidly re-established throughout the bulk of the material. There is then no preferred direction for the orientation of the cholesteric spirals so a quasi-polycrystalline structure results which is strongly scattering. Surface alignment layers are not essential for this effect, but may be used to stabilise the texture of the scattering state.

This effect has a threshold field, rather than a threshold voltage, which is determined largely by the cholesteric pitch used. It is generally found that cells which give strong optical effects require somewhat higher drive voltages than twisted nematic cells, typically 5-10V.

The visual appearance of this effect is somewhat similar to dynamic scattering, since the visual contrast is obtained between a clear, transparent state and a scattering state. Although high brightness displays are possible, the appearance depends strongly on illumination conditions and it is only in projection that good contrast is reliably achieved.

3.4 The Dyed Phase Change (DPC) Effect

This is a direct extension of the above effect which includes dyes, dissolved in the liquid crystal, to give optical absorption rather than scattering (9, 10). The dye molecules must be highly anisotropic, both physically and optically. They must align accurately with the director of the liquid crystal at all times; this is known as the "Guest-Host" effect. Also, they must be "pleochroic"; that is, their absorption spectrum should depend strongly on the relative orientations of the molecules and the polarisation of the light. Ideally, absorption should be zero when the optical polarisation is perpendicular to the long molecular axis, and strong when the polarisation is parallel to that axis, as shown in Figure 7.

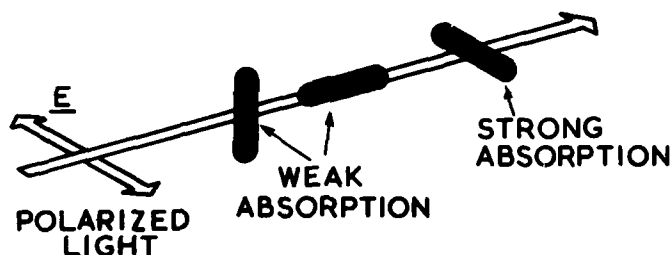


Figure 7. The anisotropic optical absorption of pleochroic dyes as used in the dyed phase-change effect.

In the driven (on) state of a DPC cell all the liquid crystal and dye molecules are forced to align perpendicular to the plane of the cell, so light passing through the cell is only weakly absorbed. In the undriven (off) state the twisted cholesteric structure ensures that all polarisations of incident light encounter sufficient dye molecules whose axes are suitably aligned to give strong absorption. As in the previous effect, the electric threshold is field rather than voltage dependent.

With a suitably designed diffuse reflector this effect is visually very attractive. It should be noted, however, that the displayed information appears bright on an absorbing background, the direct inverse of the conventional TN display.

In principle DPC displays have two major advantages over TN displays. Firstly, they do not require polarisers and therefore should appear much brighter than TN displays. Secondly, their optical properties are far less anisotropic - there is no "low voltage quadrant" - so they can be viewed clearly over a much greater angular range.

The basic cholesteric materials are made by adding small quantities of "twisting" agents to normal, wide temperature range, nematic mixtures. The temperature ranges and viscosities of the resulting mixtures are therefore very similar to those of the nematic components.

Choice of the dye component involves many considerations. Its alignment in the liquid crystal host is described in terms of an "order parameter" (10) which must as high as possible to minimise absorption in the on-state. Its absorption spectrum must be suitable, blue and black being preferred. It must be sufficiently soluble in the liquid crystal host to give adequate absorption and contrast without risk of the segregation of dye particles at low temperatures. Finally, it must be highly stable when exposed to solar UV radiation.

Exploitation of this effect was initially hampered by inadequacies in the dyes, either poor solubility, low order parameter, poor UV stability or unsuitable colour. Recently, however, a range of anthraquinone based materials has been announced (11) which combine excellent values of all properties.

The overall design and performance of a DPC display is subject to many compromises, since each variable parameter affects more than one of the observable features. For example: a large cell spacing provides good contrast, but at the expense of either slow turn-on or high drive voltage; short cholesteric pitch improves contrast and gives rapid turn-off, again at the expense of high drive voltage; high concentration of dye gives good contrast but reduces on-state brightness and may involve low temperature solubility problems. Clearly, the achievable speed, contrast, drive voltage etc, will depend strongly on the external design constraints.

Temperature affects the threshold voltage in much the same way as for a TN display. Values of dV_T/dT are of the order of -1% per $^{\circ}\text{C}$. Similarly response times are affected by changes of viscosity with temperature. However, the fundamentally faster response of the DPC effect means that usable response speeds can be retained to much lower temperatures.

The angle of view of a reflective DPC display is determined largely by the properties of the diffuse reflector. By control of the surface texture of this reflector the on-axis brightness of the display may be played off against the wide-angle appearance. Furthermore, since no rear polariser is required, the rear reflector can be located inside the LC cell, thus eliminating the shadow parallax problems discussed above, and further increasing the brightness and contrast of the display.

The same technologies for cell sealing can be used with DPC cells as with TN cells. The absence of polarisers, however, means that the DPC cell should be less susceptible to degradation in extreme environments. Although dyes of adequate performance are now available, and cell design and drive requirements are well understood, displays using this effect have not yet been exploited commercially to any significant extent. It is believed, however, that this type of display will be the natural successor to the TN display for a wide range of applications.

3.5 Birefringence Effects

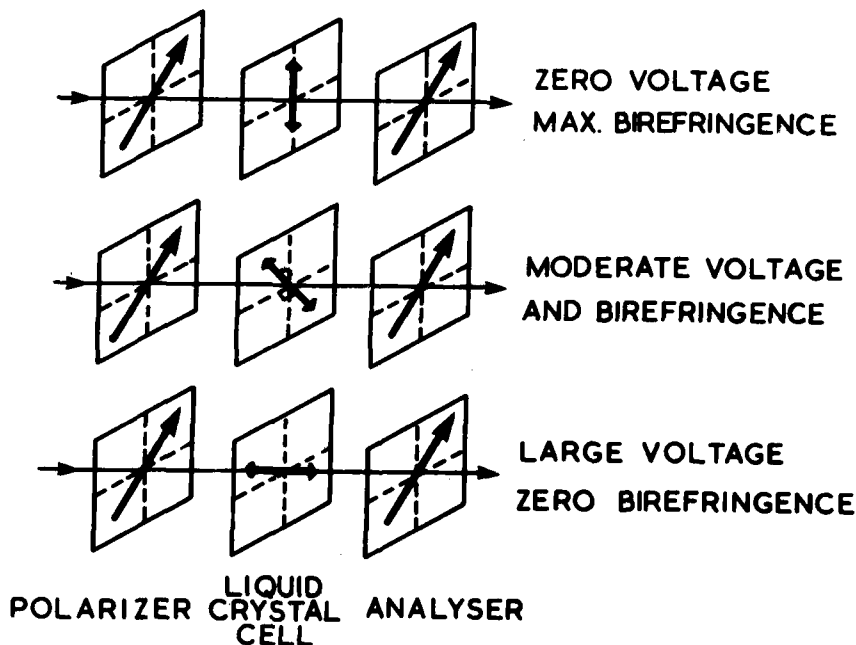


Figure 8. Typical "variable birefringence" device at various voltages.

The large anisotropy in the refractive index of aligned nematic liquid crystals permits electrical control of birefringent effects (12). An example is shown in Figure 8, where a thin layer of planar aligned liquid crystal of positive dielectric anisotropy is placed between parallel polarisers. The incident polarisation is set at 45° to the director. By direct analogy with birefringence in solid crystals the transmission may be analysed in terms of ordinary "o" and extraordinary "e" rays polarised perpendicular and parallel to the director respectively. For certain wavelengths of incident light the optical path difference between o and e rays through the liquid crystal will be an integral number of wavelengths and the resultant will pass unhindered through the analyser. For all other wavelengths the light emerging from the liquid crystal will be elliptically polarised, to greater or lesser extent, and will therefore be partially or even completely absorbed by the analyser. Thus, in general, the transmitted light will be coloured. When an electric field is applied the

director rotates changing the degree of birefringence and consequently altering the transmitted spectrum. In the limit, for very high fields, the director becomes normal to the plane of the cell and birefringence is reduced to zero.

A similar effect is obtained with negative dielectric anisotropy material in a cell with nearly homeotropic surface alignment. With zero applied volts there is no birefringence and therefore no transmission between crossed polars. As the applied voltage is increased the molecules tilt *away* from homeotropic and the birefringence rises. Provided this tilt is in a plane at $\sim 45^\circ$ to the polarisation direction this birefringence results first in increasing transmission of white light, followed by a series of colours at higher fields.

These effects are also field rather than voltage dependent, so to obtain uniform effects over large areas requires extreme skill in constructing cells with flat and parallel faces. Effects of this type have only received a limited amount of attention both for alphanumeric displays, electrically controlled colour filters and for light-valve projection displays.

3.6 Smectic Effects

Smectic materials have the most orderly structure of all liquid crystal phases. Not only do the individual molecules tend to align parallel to each other as in nematics, but they are also arranged in a layered structure. Depending on the detailed arrangement of molecules in the layers, several distinct smectic phases (S_A , S_C , S_B etc) have been defined. The common feature of most smectic materials is that their viscosity is very high compared to nematics. Consequently, any molecular alignment tends to be stable, since the realignment forces due to surface treatments do not propagate far into the material - the basis of memory effects. Furthermore, very large electric fields are needed to realign smectics, except at temperatures very close to the nematic or isotropic phase boundary. Mixtures of materials have been produced with very wide smectic temperature ranges, and recently these materials have been exploited in a variety of ways for display purposes. Here we shall describe thermal-electrical, dynamic scattering and ferroelectric effects.

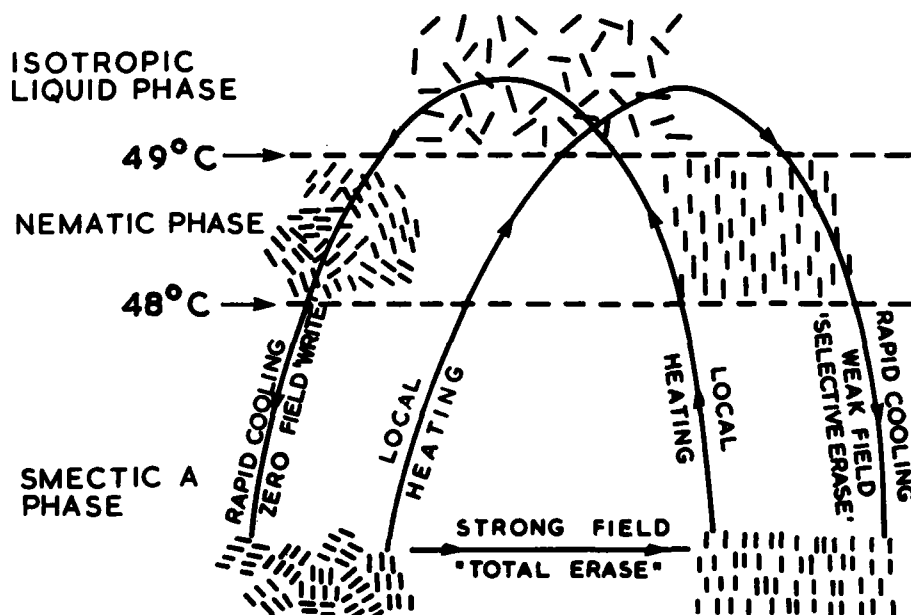


Figure 9. Schematic representation of phase and structure changes involved in the thermal-electrical effect in Smectic A materials.

The thermal-electrical effect is illustrated in Figure 9. At temperatures well below T_{SN} (the smectic to nematic phase boundary) the material can exist in either of two states; a "homeotropic" aligned state which is clear and transparent, or a "focal conic" state which is strongly scattering. Reversible transitions between these states are obtained by a combination of heat and electric fields. When the temperature is raised the material passes through the nematic into the isotropic phase, where all molecular ordering is lost. If it cools rapidly into the smectic phase this disorder tends to be frozen in and the strongly scattering, focal conic state is established. If, however, an adequate electric field is applied during cooling, the molecules are realigned in the nematic state, and this realigned state is frozen in. All regions of the cell which are not heated are virtually

unaffected by this realignment field, so stored data may be selectively changed without the need to re-write all the information.

In one type of application a focussed laser beam is scanned across the cell to provide the local heating. Both cell plates are coated with transparent electrodes for application of the "erase" field. Total erase of all information is obtained by applying a large electric field. These devices are generally used in projection displays, having the advantage that write and erase can be performed while the cell is in the projector. The laser-written lines can be very narrow, 10 microns or less, so very high resolution is possible. Systems using various lasers and projection systems have been described in references (13), (14) and (15), giving up to 10,000 lines resolution; reference (16) describes a 3 colour system with 2000 lines resolution using 2 smectic cells. Generally these systems are bulky and consume a lot of power, but moderately compact, transportable versions have been developed. This type of display is ideal for superimposing dynamic information onto projected maps.

An alternative thermal electrical approach uses matrix addressing (17). The row electrodes act as resistive heaters, so when a current pulse is passed through one row that entire row of picture points is heated into the isotropic phase. Voltage pulses are applied during cooling to selected column electrodes to realign appropriate elements. The column pulses of course affect only those elements that have been heated, so cross-talk is absent. Hareng et al (18) described a laboratory demonstration using a 1 cm x 1 cm silicon slice as substrate. The display was used in projection and the 256 lines were refreshed at TV frame rates. A larger version, measuring 94 x 90 mm with 250 x 240 lines, has been developed on a glass substrate for computer terminal applications. The line address time of 20ms implies a total frame time of 5s. The operating temperature range was 5°C - 40°C, with peak heating power of 15W. A somewhat similar device (19) used a dichroic dye dissolved in the smectic material to try to improve the visual appearance. The operating principles were very similar, but a bright diffuse reflector was placed behind the cell so that visual contrast was obtained between the clear state (bright) and the scattering/absorbing state (dark).

The dynamic scattering effect has been used in a smectic display by Crossland et al (20). When dopants were added to reduce the material's resistivity it was found that low frequency AC fields of adequate amplitude induced scattering, whereas high frequency fields induced homeotropic (clear) alignment. Similar transitions were also obtained with carefully controlled DC pulses, suitable for matrix displays. It was shown that pulse conditions could permit addressing of an infinite matrix in the line-at-a-time manner, and the addressing of a 500-line display was successfully simulated on small matrix. Drive voltages increased as the line address time was reduced, typical values being from ~ 100V at 100ms to 185V at 5ms.

All the effects described so far have used Smectic A type materials. A notable effect has been discovered in a twisted Smectic C material where ferroelectric properties are apparent (21). Because of its ferroelectric properties this material was sensitive to the direction of an applied DC electric field. The devices could be reversibly switched between two transparent states having different birefringent properties, which, when viewed between a pair of polarizers, produced good visual contrast. The unique feature of this phenomenon was its response speed which was less than 1ms in very thin cells. To date only comparatively small test structures have been demonstrated.

4 COMPLEX DISPLAYS

4.1 Matrix Addressing

A complex display is arbitrarily defined here as one to which the number of connections is less than the number of individually selectable display elements. For a numeric display using the 7-bar format, a row of ten digits requires at least 70 elements. To supply a driver and connecting wire to each of these elements is obviously uneconomic. For alpha-numeric displays, where each character requires at least 35 dots, the problem is far more severe. The obvious solution is to use a matrix addressing method. The transparent conductors on both cell plates are patterned so that each electrode is shared between several display elements. The behaviour of this arrangement is electrically equivalent to that of a rectangular matrix of n -rows and m -columns, the cross-points representing the display elements. The minimum number of connections is obtained when $n=m$, but even with $n=3$ the number of connections to the above 10-digit example is reduced from over 70 to less than 30.

A simple way of addressing a matrix display is shown in Figure 10. The rows of the display are scanned repetitively in sequence by a "row select" pulse of amplitude V_R . While each row is selected the appropriate "select" and "non-select" data pulses, of amplitude $\pm V_D$, are applied to the columns. In the vast majority of liquid crystal effects, with the exception of the "memory" effects discussed in Section 3.6, the LC elements respond to the RMS of the difference between the row and column waveforms. Net AC drive is achieved either by reversing drive polarity after each scan or by replacing each pulse by an alternating waveform.

The problem now arises that supposedly "off" elements experience a significant drive voltage, largely composed of the data pulses to all other elements in the column. The ratio of RMS voltages applied to "on" and "off" elements, and therefore the display contrast, may be maximised by correct choice of V_R and V_D . Alt and Pleshko (22) have shown that, for a display consisting of n rows, maximum voltage ratio is achieved when $V_R = \sqrt{n} V_D$. This relationship is very important for large values of n , but for values of n around four a convenient solution is $V_R = 2V_D$.

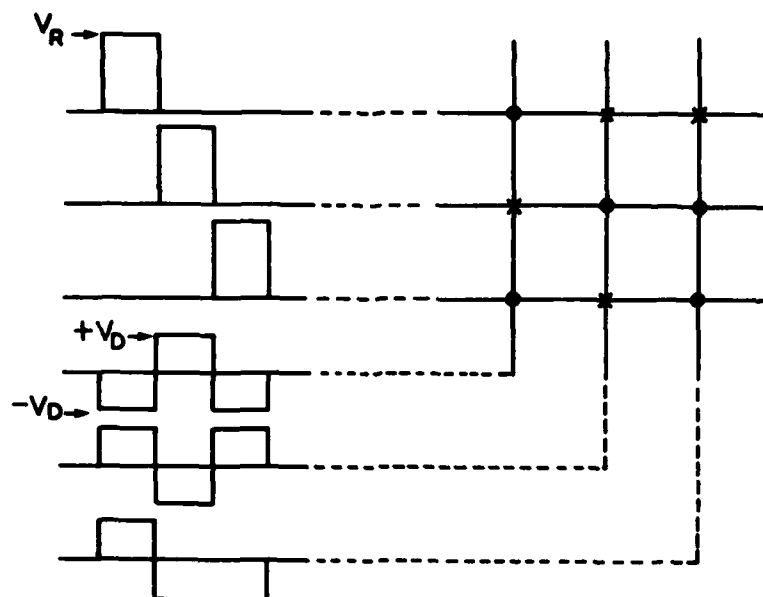


Figure 10. Multiplex drive scheme for a 3 x 3 matrix. Scanning pulses, V_R , applied to rows; data pulses $\pm V_D$, applied to columns. Polarity reversal for AC drive not shown.

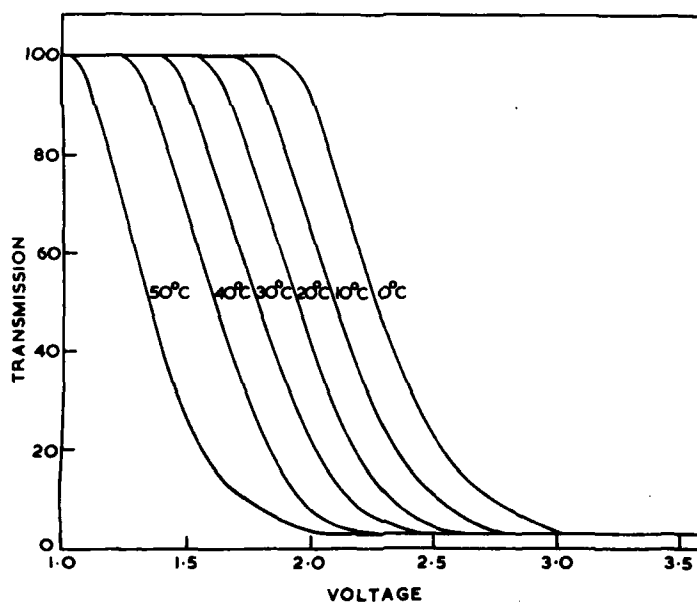


Figure 11. Variation with temperature of transmission vs voltage curves of a TN cell between crossed polars. Note the reduction of threshold voltage with increasing temperature.

The importance of this optimisation is apparent when the liquid crystal characteristics such as acceptable contrast, angle of view and temperature range are considered. Figure 5 showed the transmission versus voltage at both normal incidence and 45° from normal in the low voltage quadrant of a TN cell. Figure 11 shows normal incidence transmission plotted against voltage over a wide temperature range. Satisfactory viewing over a wide angular and temperature range requires:

- a) the value of V_{OFF} must be below threshold at the most oblique viewing angle at the highest temperature;
- b) the value of V_{ON} must give adequate absorption at the steepest viewing angle at the lowest temperature.

The multiplexed performance of a display at a fixed temperature therefore depends on the steepness and angular dependence of the threshold curve of the material used, which may be characterised by various figures of merit. For example, the ratio of voltage giving 10% transmission at normal incidence to voltage giving 90% of maximum transmission at 45° incidence immediately shows how many lines may be multiplexed at that temperature. The material E7 mentioned earlier, which was not designed for multiplexing, has a figure of merit of about 1.9 which is scarcely adequate for even 3-way multiplexing with full contrast over this angular range. It should be noted that the lower is the value of this figure of merit, the more lines can be multiplexed. Materials have been developed giving merit values below 1.6, and it is found that reasonable performance is obtained in displays with up to 32-lines.

The large values of dV_c/dT of all liquid crystal materials preclude multiway multiplexed operation over a wide temperature range with fixed drive voltages. Accurate methods for temperature compensation of drive voltage have been developed which can maintain the visual appearance of displays over practically the entire temperature range that the material is liquid crystalline. These methods either involve a thermistor or other temperature sensor mounted close to the display cell, or may use the liquid crystal material as its own temperature sensor. This latter method (23) makes use of the dependence of liquid crystal capacitance on temperature and voltage, and has the advantage of sensing temperature at exactly the right place and with no time delays. In spite of the achievable accuracy of temperature compensation it is still advantageous to use materials with small temperature coefficients in order to minimise the effects of temperature gradients across the cell.

To date, commercial alphanumeric displays have been produced using up to 32-way multiplexing of reflective TN cells. At this level of multiplexing the angle of view for good contrast is quite limited, but temperature compensation of drive voltages permits operation from 0°C to ~ 50°C. The display format is 8 rows of 40 alphanumerics, which may be used as a 64 x 320 dot graphics display.

The electrically controlled birefringence (ECB) effect discussed in Section 3.5 can be arranged to give a rather steeper optical response curve. This has been exploited by Schadt (24) who demonstrated a 35 x 60 line alphanumeric display and by Maltese et al (25) who developed a 160 x 160 line TV or alphanumeric version, both used in the reflective mode. It appears that a major problem was that very thin cells (~ 5µm) were required, with better than ± 0.3µm spacing homogeneity to assure acceptable uniformity of appearance.

So far there has been little exploitation of other display effects, such as dyed phase change, in complex displays, largely due to the poor steepness of the electro-optic threshold curve.

To make further progress from this situation there are five main avenues that have been followed in various laboratories:-

- a) Restrictions on the optics of the display;
- b) Improvements in materials for use in established effects;
- c) Improvements in drive methods for conventional liquid crystal effects;
- d) Exploitation of new liquid crystal effects whose characteristics are better suited to multiplex drive;
- e) Incorporation of electrical components at the matrix cross-points of display cells.

4.2 Displays with Restricted Angle of View

When reduced angle of view is acceptable, or when projection is used, more complex displays are possible. One of the most complex was reported by Hitachi (26) where a 120 line TV picture with 160 dots per line and 16 grey levels was demonstrated. The TN effect was used, and the entire TV receiver and display consumed about 5W from a 15V supply. One must assume, however, that since 60-way multiplexing was used the angle of view and temperature range of the display must both have been extremely narrow. More recent versions of this display (27) have used a far more complicated electrode structure known as a "quad-matrix", so that the 120 x 160 picture points can be driven as a 30 x 640 matrix.

Another TV-type demonstration was by Robert (28) who used the variable birefringence effect in a negative nematic material as mentioned in Section 3.5. To satisfy the severe tolerance on cell spacing that this effect incurs, the active cell area was restricted to 6.4mm square. A 10 cm square image was then produced by projection. The display consisted of a 128 x 128 dot matrix with 8 grey levels. The response speed at room temperature permitted only 5 images per second, but this rate doubled at 40°C.

4.3 Improved TN Materials

There is considerable commercial pressure for improved materials for multiplexed displays, and it is clear that gradual improvements are continually being made. However, a major breakthrough would be required to improve the threshold sharpness to a value that would permit multiplex drive for, say, 25 rows of alphanumeric characters - a typical VDU requirement. Even greater improvements are needed for dyed phase change displays.

4.4 Improved Addressing Waveforms and Restricted Information Displays

The Alt and Pleshko optimisation of drive voltages mentioned in Section 4.1 assumed a rather restricted type of waveform where only one voltage ratio was adjustable and where the addressing waveforms depended in a very simple way on the data to be displayed. Several authors (29) have recently considered the potential of completely generalised drive methods. The conclusions of these theories are that, in general, improvements are possible, but these improvements are only significant either when the number of scanned rows is very small or when the number of elements per column which are different from the background is very small. Clearly, neither of these conditions pertains to complex alphanumeric displays, but two situations where this approach has been used are in bargraph displays and oscilloscopes.

A digital bargraph display consisting of a single column of dots would normally display data by having all dots below the indicated level on, and all dots above that level off. A liquid crystal display of this type has been described by Kmets (30) in which the connections between elements were configured to be electrically equivalent to a conventional matrix. This matrix required few external connections and very few distinct drive waveforms. Nevertheless, the 3:1 voltage ratio between on and off elements ensured high contrast viewing over a wide angular and temperature range. Further extension to the multiplexed drive of double and triple bargraphs was demonstrated with only slightly degraded visual appearance.

The oscilloscope scheme of Shanks et al (31) utilised the fact that, when displaying a single-valued function on a matrix display, only one element per column is different from the rest. In practice it is convenient to turn the background elements on and hold the data elements off. The method used a set of different waveforms, one per row, driving the matrix continuously. To obtain an off element at any required row and column intersection it was merely necessary to apply to the column the same waveform as was applied to the row. The pseudorandom binary waveforms chosen here had the advantage that a high, uniform voltage was applied to all on elements giving good contrast and permitting very wide temperature range operation. The entire oscilloscope with 100 x 100 dot display required only 60 integrated circuits and consumed less than 500mW. It was demonstrated in reflection with both TN and DPC displays, while one model used a transmissive TN display for large scale projection. A commercial version with a 128 x 256 element DPC display has recently been introduced.

4.5 Alternative Liquid Crystal Effects

Although there are many liquid crystal effects that might eventually be exploited in this way, the three effects mentioned here have been chosen largely because of existing demonstrations of their capability.

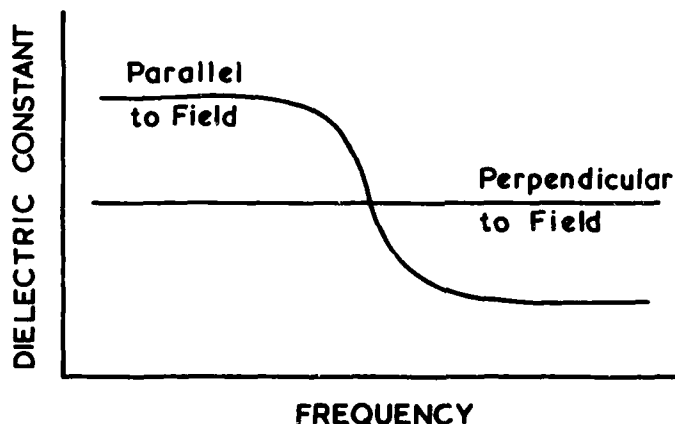


Figure 12. "Two-frequency" nematic material; variation of the principal dielectric constants with the frequency of the applied electric field.

The first, known as "two-frequency multiplexing", uses the optics of a conventional TN display, but incorporates nematic materials having unusual dielectric properties. Figure 12 shows the variation of the principal dielectric constants with applied frequency. There is a critical frequency f_c , known as the "cross-over frequency", at which the two values are equal. Below f_c , the parallel dielectric constant exceeds the perpendicular so a low frequency field tends to turn the display on. Above f_c the reverse is true, so a high frequency field tends to turn the display off. A few useful materials exist having f_c in the range 1-10 kHz at room temperature.

This effect has been exploited by van Doorn and de Clerk (32) and by Hosakawa et al (33). In both cases high and low frequency drive signals were applied simultaneously. The selection of on and off elements was done via the high frequency signals. The low frequency signal, of constant amplitude, effectively counterbalanced a large part of the effect of the high frequency signals. It can be shown that, provided the ratio of various signal amplitudes is correctly controlled, the number of

lines that can be addressed increases proportional to the applied voltages. A detailed analysis of the optimisation of drive for this effect has been presented by Clark et al (34), who proposed a figure of merit similar to that of the conventional TN figure of merit introduced in 4.1.

The main problem with this method is the variation of f_c with temperature; typically f_c doubles with every 8°C rise. Consequently, the total temperature range of the method is restricted to maybe 40°C by the range of practicable drive frequencies. The demonstration of this method by Hosakawa et al (33) used 56-way multiplexing to generate 8 rows of 64 characters. Drive amplitudes were restricted to 40V peak-to-peak, and the temperature range covered was 0°C to 40°C .

The second method, developed by Tani et al (35), exploited the hysteresis and storage effects sometimes found in the characteristics of the cholesteric-nematic phase change effect. Both clear and scattering states were obtained that remained stable for several hours at room temperature, and a method was achieved of switching between these states in a few milliseconds. The largest display consisted of 306 lines of 574 dots at 0.4mm pitch and was driven with $\pm 14\text{V}$. The contrast ratio was 24:1 and the angle of view was greater than $\pm 70^\circ$. Unfortunately no information was given on the temperature range of these displays.

The third method, recently discussed in (36), uses a new type of bistable twist cell filled with a cholesteric material. It is found that when the correct values of cell spacing, cholesteric pitch and surface alignment are chosen, there are two stable configurations of the LC director having markedly different optical properties. Visual contrast is obtained either using crossed polars as in the TN effect, or using dissolved pleochroic dyes. The bistability ensures that an indefinitely large matrix may be addressed without cross-talk problems, although demonstrations have been restricted to 8×8 element test cells so far. Cell spacing uniformity is important and dust particles cause problems, but since this work is at an early stage it is difficult to assess the severity of these problems.

4.6 Incorporation of Integral Electronic Components

The advantage of this approach is that it makes only minimal demands on the steepness of the transmission-voltage characteristic of the liquid crystal. The complexity now resides in the cell substrate, where an electrical device, either active or non-linear passive, is placed in series with each liquid crystal element. The electrical characteristic of each device must achieve two objects; firstly, it must block all partial select pulses addressed to other elements; secondly, when a full select pulse occurs it must permit the capacitance of the liquid crystal to charge up rapidly, and when this pulse ends it must prevent the charge leaking away until the next select pulse occurs. Several different types of device are currently being exploited including active silicon substrates, thin film transistors made with various active materials, Varistors, and metal-insulator-metal thin film devices.

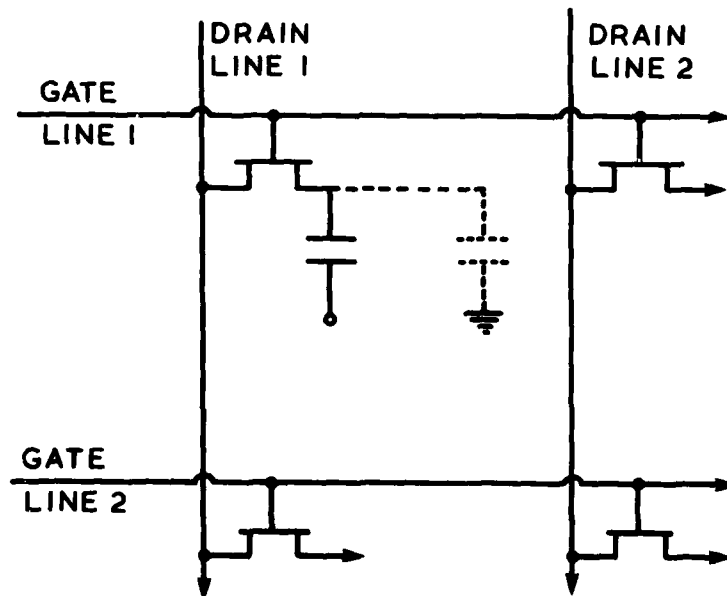


Figure 13. One element of a liquid crystal matrix with integral FET addressing. The additional capacitor is not always required.

In the Si substrate approach one plate of the LC cell consists of a large Si slice operating as a single integrated circuit. The operation of each display element is sketched in Figure 13, where the LC is represented by a capacitor and is driven by a single FET. The FET gates are connected to row bus-bars, and the sources to column bus-bars. Transistors are turned on one row at a time by a pulse on the appropriate gate line, while video data is applied to the columns. The

capacitance of the LC plus the storage capacitor then charges to the video voltage, and this charge is stored while all other rows are addressed. AC drive is obtained by periodically reversing the video polarity. Any reflective mode optical effect can be used, such as dynamic scattering, dyed-phase change, etc, but twisted nematic is not possible because a rear polarizer cannot be incorporated. In 1978 Lipton et al (37) demonstrated a 1.75" square prototype having 175 x 175 elements using dynamic scattering. Subsequent developments in various places have incorporated some of the decode and drive circuitry around the periphery of the display, thus reducing interconnection problems and the complexity of the external circuits. For example, Kasahara et al (38) presented a 220 x 240 element TV display with 2" diagonal that included integrated gate-bus drivers. Hosokawa et al (39) made use of pleochroic dyes to improve the appearance of a similar display. Ymasaki et al (40) developed a 240 x 240 element TV display requiring only 12 external connections. This type of display will undoubtedly find many applications and has clearly not reached its development limit, but it will always be limited by the maximum size of Si slice available. Attempts have been made to produce larger displays by butting together 4 slices in a single display, but this was not very successful.

The thin film transistor approach is electrically very similar, in that each display element is addressed via a FET, but it has the great advantage that the substrate is a glass sheet on which all components are vacuum deposited; the size limitation of the Si slice is eliminated. The work of Luo et al (41) was based on a 6" square display with up to 180 x 180 elements. The semiconductor was CdSe, produced in polycrystalline form by vacuum evaporation followed by careful annealing. In this case the TN effect was used, but in principle any other liquid crystal effect could be used. Both alphanumeric and video display modes were demonstrated, the video being refreshed at 60 Hz and achieving 6 shades of grey. More recent work (42) reports displays of up to 5" x 5" with 50 lines per inch made by an improved, high yield manufacturing process.

Many semiconducting materials have recently been assessed for this application including Te(43), recrystallised poly-Si(44), and amorphous silicon (45, 46). The amorphous Si approach is particularly attractive since the deposition and processing steps are all comparatively simple. The other approaches result in higher mobility semiconductors which may permit the decode and drive circuits to be fully integrated, but they require more critical processing. It remains to be seen which of the many possibilities is best suited to the LCD application.

An interesting alternative approach used a sheet of ZnO "Varistor" material as one plate of the LC cell. Arrays of discrete varistor devices were then defined by the electrode and insulator geometries. The I-V characteristic of a Varistor in series with a liquid crystal element is sufficiently non-linear to eliminate the majority of the cross-talk problems of matrix drive, effectively producing a very sharp threshold. Castleberry et al (47) produced a 5" x 7" array with 180 x 252 elements controlling a dyed phase change liquid crystal. Drive voltages of around 50V were required, and the major problem encountered was non-uniformity of breakdown voltage of the individual varistor elements.

Streater et al (48) have developed metal-insulator-metal (MIM) thin film devices having similar, highly non-linear, I-V characteristics. Arrays of these devices can be deposited on glass substrates permitting use of various liquid crystal optical effects. A prototype device array, 3" x 4", having 128 x 160 elements was successfully operated in a TN liquid crystal display cell. The manufacturing processes involved only 3 photolithographic masks, but required very careful control of the properties of the active materials. To date only alphanumeric and graphic operation has been demonstrated.

The final approach discussed here returns to the single crystal Si substrate, this time using a Charge Coupled Device (CCD) shift register to accept video inputs directly (49). In this device the CCD shift registers are on one face of the high resistivity Si slice, the stored charge being coupled through the slice to excite the LC cell on the opposite face. A prototype device measuring 5 x 5 mm with 256 x 256 elements has been developed, but at present the observed resolution is only 125 x 125 elements. Larger devices, up to 1000 x 1000 elements, are planned for use as light valves in various projection displays and optical processing applications. This display is in fact the third in a series of developments for the same applications. The first two types used LC cells that included a photoconductive layer, the state of the liquid crystal being locally controlled by the illumination of the photoconductor. The original device (50, 51) used CdS as the photoconductor which was illuminated by an image of data displayed on a bright, high resolution CRT. Various liquid crystal optical effects were used to modulate the illumination from the projection lamp. The second device (52) used a Si slice both as the photoconductor and as one plate of the liquid crystal cell. In both cases high resolution was obtained and high brightness image projection was possible.

5 CONCLUSION

Over the last ten years or so liquid crystals have provided us with a wealth of electro-optic effects suitable for display applications. No doubt many more await discovery and exploitation. To date only the Twisted Nematic effect has been extensively and successfully exploited, particularly for small numeric and alphanumeric displays. This effect is by no means ideal for all applications; it is slow at low temperatures, its angle of view and brightness are poor, it is unsuitable for high level multiplex drive, etc. Its chief merits, however, are its simple, reliable and cheap construction, its low voltage and power requirements and its reasonable performance in either transmission or reflection. A vast number of approaches are being explored to improve on this situation, some to make incremental improvements to established displays, others to develop radically new devices and effects. The rate of progress in research is considerable, but there will be few short cuts towards the development of high complexity displays adequate for the full military environment. We may look with some confidence, however, towards a considerable increase in the capability and range of applications of liquid crystal displays in the next few years.

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ELECTROLUMINESCENT DISPLAYS

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3.6 ELECTROLUMINESCENT DISPLAYS

3.6.1 HISTORICAL SURVEY

Electroluminescence (EL) is defined as the light generated by a phosphor under the influence of an electric field. Depending upon the phosphor material and electrode geometry, light may be generated by an alternating (ac) or continuously applied (dc) field. For each type, the devices may be fabricated with powder EL or thin-film EL materials.

One cause of light emission is related to the energy released upon recombination of minority and majority carriers in a solid at recombination centers. Alternately, the emission is due to impact excitation of luminescent centers by charge carriers which have been accelerated by high electric fields within the solid. The first process is that of light emitting diodes and is called injection-luminescence (see Section 3.5). The second, which does not require a perfect crystal and works well for either ac or dc, is called electroluminescence. The variety of EL devices (ac or dc, powder or film) arises from different means of achieving the high field and protecting the device when avalanching occurs.

Significant advancements in the state of the art of EL displays have been achieved during the past decade. Although powders have much improved and are used in certain aircraft applications, the main breakthrough has been in thin-film phosphors. Being highly transparent allows for the use of an absorbing black rear layer for contrast enhancement. Highly non-linear in its luminance versus applied voltage relationship, the thin-film EL allows for direct matrix addressing. Because the ac thin-film EL (TFEL) devices currently represents the greatest investment in time and money and to many, having the most potential, sections 3.6.2 through 3.6.6 will focus principally on ac TFEL. The powders and dc thin-films will be discussed in Section 3.6.7.

The electroluminescence (EL) phenomenon was first discovered by Destriau in 1936, in zinc sulfide (ZnS) with copper (Cu) used as an activator (3.6.1). This discovery led to several efforts to apply the EL phenomenon to lighting. During the 1950's and 1960's, extensive research was carried out to fabricate EL displays using phosphors made by heating (fusing) ZnS:Cu powders. The powdered EL, however, could not be made daylight readable, nor could the brightness levels achieved be maintained for even moderate lifetimes. The limited life resulted from the migration of the activator (Cu) under the influence of the applied electric field. Further, the mechanism of destruction was fast, even at moderately high temperatures. Transparent thin-film phosphors had been made as early as 1934 by DeBoer and Dippel (3.6.2), and later good quality films were made by

Williams in 1947 (3.6.3), and Feldman and O'Hara in 1954 (3.6.4), though not for EL display applications. The earliest thin-film EL phosphors were devised by Thornton (3.6.5) in the late 50's, while the matrix addressing concept for EL panels was patented in 1955 by Piper (3.6.6).

Of the various thin-film devices being developed for display application, the most advanced in terms of practical characteristics is certainly the three layer, double insulated, ac coupled, ZnS:Mn thin-film device first developed by Soxman (3.6.7) (see Fig. 3.6.1). In this configuration, which is now the standard construction, the active light-emitting layer is sandwiched between two transparent high-dielectric-strength layers, and interposed between thin-film electrodes, at least one of which is a transparent electrode on a transparent glass substrate. When viewed from the front, the substrate is transparent through to the rear electrode. The front and rear electrodes are perpendicular to each other to form a crossed matrix pattern.

In the late 60's, Soxman reported on reproducible ac thin-film matrix EL devices having over 50 cd m^{-2} and several thousand hours of life (3.6.7). However, because the rear electrodes were reflective, the contrast ratio was poor. It was suggested that if the rear electrodes could be made transparent and backed with a diffuse black material, or if the second dielectric layer were to be made highly absorbing, the unexcited device could appear quite black, thus providing good contrast in high ambient illumination (3.6.8) (Fig. 3.6.2). The advantages of the black layer were explored by several other researchers during the mid 60's using powders and thin-films (3.6.9-3.6.11). The first thin-film EL display with a black layer was produced in the 1960's by Soxman and Steel (3.6.7 & 3.6.11) who reported on some samples having in excess of 160 cd m^{-2} luminance with flat maintenance (see 3.6.3.2). Major advances were reported at the 1980 SID International Symposium in San Diego. Inoguchi et al (3.6.12) presented data on a three layer thin-film ZnS:Mn EL display exceeding 10,000 hours of life at 340 cd m^{-2} luminance with flat maintenance. Mito et al (3.6.13) presented a second paper describing the reproduction of TV imagery on a 108 x 81 line TFEL panel. However, these displays did not include a black layer. Because they used reflective aluminum rear electrodes with a front-mounted circular polarizer for contrast enhancement, the performance was marginal. The performance of thin-film EL devices using ZnS:Mn, as demonstrated by Soxman, and Inoguchi et al, has since been confirmed by others (3.6.14 & 15).

3.6.2 PRINCIPLES OF OPERATION

The thin-film electroluminescent display is, as described above, made up of a sandwich-structure of conductors and dielectrics with a luminescent phosphor in the center. The thin-films are deposited on a glass substrate, usually starting with an Indium Tin Oxide

transparent conductor followed by a dielectric of high electrical breakdown strength, followed by the manganese-doped zinc sulfide phosphor, the second dielectric, and finally, the rear conductor. As stated earlier, a black thin-film layer may be incorporated to the rear of the zinc sulfide phosphor before the rear dielectric or may be used as the rear dielectric. The basic principles of operation are as follows: While the mechanism is not well understood, it is generally agreed that when a high electric field (up to $1-2 \times 10^5 \text{ V cm}^{-1}$) is applied to the sandwich structure, the ZnS layer, also a dielectric, breaks down into avalanche conduction, and current flows through it to the encapsulating dielectric interface. As the charge builds up on the dielectrics, the internal field in the ZnS is reduced, and conduction ceases until the field is reversed. Thus, one has a pulsed avalanche conduction of the ZnS for each field reversal. The breakdown in the ZnS is apparently initiated by electrons tunneling out of the interface sites into the conduction states of the ZnS. At the very high fields involved, the electrons excite the manganese atoms, and photons are emitted, i.e., luminesce, with a characteristic yellow-orange (585 nm) emission. To prevent destructive breakdown under normal operation, the encapsulating dielectrics should not conduct until the field reaches levels of $10-14 \times 10^5 \text{ V cm}^{-1}$. Should breakdown occur in the encapsulating dielectric layers, a destructive runaway current could flow through the entire structure, causing partial burnout of the active layer. Moreover, since the stored energy is larger, catastrophic failure can also occur (See section 3.6.3.3).

For some time, the phenomenon was considered to be due to ionization. Vlasenko and Yaremko (3.6.16) investigated ac electroluminescence of ZnS:Mn films as a function of thickness between 0.04 and 2μ . Below 0.1μ , the emission dropped very rapidly. Thus, they concluded that the excitation mechanism was impact ionization by accelerated electrons in the conduction band. Now, there is general agreement (3.6.17) that light emission from ZnS thin-films is due to electron impact excitation of the Mn activator.

The processes of tunneling and impact excitation are both very non-linear with respect to the applied field. These help give the luminance vs voltage variation and an unusually strong steepness and threshold behavior, thus greatly facilitating multiplexing (Fig. 3.6.3).

If one examines the "lighting" of a pixel under high magnification, "filamentary conduction" is observed. As the field is increased to the point where the initial emission begins, it is seen that emission is not uniform, but that little streams (filaments) of light can be observed: some fixed, at the lowest threshold levels; some wandering, at slightly higher threshold points. As the voltage is increased, the pixel emits over more of its area and can appear mottled until the higher field causes the entire pixel to emit. If the applied voltage is a square wave with an extremely fast

rise time, this phenomenon may not be observed. It can be assumed that since some non-uniformity exists in any pixel, some filamentary conduction will always take place at turn-on.

3.6.3 PHYSICAL CHARACTERISTICS

3.6.3.1 Size

The actual panel size of an ac TFEL is constrained by the need to provide a hermetic seal and electrical connections around the periphery. At least 1.0 cm must be provided to the length and width of the active area. The depth of panels is usually less than 1.25 cm. The addition of a Thin-Film Transistor (TFT) drive (See Section 3.6.4) will not appreciably affect the depth. However, if MOS circuitry is rear-mounted, an additional 0.3 cm may be required.

3.6.3.2 Life Expectancy

Although "half-life" has often been used to describe the expected usefulness of flat panel displays, TFELs evidence a unique characteristic, due to "burn-in" or annealing. The annealing process probably results from a redistribution of luminescent centers. The burn-in establishes and maintains a higher luminance level than when first activated (Fig. 3.6.4)(3.6.18). Once established, this level can be maintained as a linear function by minor voltage adjustments, sometimes called maintenance or flat maintenance. Fig. 3.6.5 shows the effect on a device which had not experienced burn-in. Life tests have demonstrated that an MTBF of 10,000 hours is readily achievable.

3.6.3.3 Reliability

The reliability of ac TFEL devices not only depends on the quality of the polycrystalline manganese-doped ZnS layer, but the quality of the dielectric layers, as well. Since the light output of the device is directly proportional to the charge flowing through the capacitive layers per pulse, the number of pulses per second, and the voltage across the ZnS film, higher reliabilities can accrue if high dielectric constant and breakdown strength insulator films are used (3.6.19). Caution must be considered in the sealing of the sandwich, since the TFEL structure demonstrates considerable sensitivity to moisture (extreme in the cases which employ Y_2O_3 as a dielectric). The devices must be passivated in some way to avoid progressive destruction of the device through a process of area breakdown delamination, or peeling of the film. On the other hand, recent work by Suntola, using atomic epitaxy deposited thin-films, has evidenced structures so dense and uniform as to be seemingly insensitive to moisture and, except at

the edges, to require minimal sealing (3.6.20). Small burn-outs can occur at pinholes in the dielectrics because of high current conduction. When the high current conduction occurs, the conductor acts as a "fuse" and the circuit burns open, thus limiting the degree of destruction. This fusing action is very helpful in the overall performance of the display since it blocks the possibility of catastrophic failure. The atomic epitaxy deposition appears to minimize, although not eliminate, this problem (3.6.20).

Another characteristic of thin-film EL devices is a relationship between localized failure mode and active device area, a relationship which is critically dependent upon the electrode materials and thickness, as well as upon the choice and perfection of the dielectric layers. Breakdown is a nonlinear phenomenon. Once initiated at some defect in the dielectric layer, the stored energy available to produce destructive local heating is proportional to the contiguous active device area. Unless the electrode restricts or constrains the lateral flow of energy, catastrophic failure may result. This is one of the major problems in this technology, because, considering the high fields involved, it is not yet feasible to make very large areas totally free of local breakdowns. Suntola has proposed slotting the electrodes at the line intersections as a means to control the lateral destruction (3.6.21).

Another important factor is the possible contamination of the materials. Efficient luminescence with an Mn^{+2} activator employs a ten times higher concentration than with Cu or Cl activators. The practical significance is that the Mn activated phosphor system is less affected by impurity contamination; i.e., given the same order of contamination.

3.6.3.4 Memory

A potentially useful memory effect has been observed in ac TFEL devices which have an appropriate thickness and manganese doping. When the applied voltage is first increased, the light output in a memory device increases nonlinearly as a non-memory device would (3.6.22); however, as the applied voltage is reduced, the light output tends to remain at a high level (which depends on the magnitude of the highest prior applied voltage). A memory display panel of 1248 characters (5x7) has been demonstrated (3.6.23). Using this effect, one can also obtain grey scale with memory by using (switching) voltage amplitude modulation in the matrix address mode. This hysteresis behavior can also be triggered by light as demonstrated by Suzuki et al (3.6.24). More recently, driving techniques have been developed such that an ac TFEL memory panel, operated as a video display panel, can have a stop motion or frame store capability (3.6.25). Furthermore, in a storage display mode, the information may be electrically read out by applying a reading pulse to sense the state of each cell (pixel) (3.6.26). The major importance of the memory effect is that it can significantly reduce the demand on the luminous efficiency of the ac TFEL

device since it obviates the need for refresh. On the other hand, the long-life characteristics typical of the non-memory panel have not been demonstrated in the memory version. The stability of the memory operation is also one of the critical problems still under investigation.

3.6.3.5 Efficiency

The efficiency of the EL is strongly dependent on the Mn concentration. The efficiency of the driving circuitry must also be considered. Typical luminous efficiencies of ac TFEL panels are in the range of 1 to 2 lumens per watt, with values of 5 and 9 lumens per watt having been reported (3.6.21 & 3.6.27). At 2 lumens per watt, a 15 cm square panel, with typically 20% of that area in actual use, will consume about 185 mw for a 32 cd m^{-2} luminance (sufficient for sunlight legible alphanumeric and graphics, but not grey scale video). Since the line driver technology now being used can dissipate up to forty times that power, this can result in a total power consumption of as much as 7 watts. In essence, while display efficiency is obviously important, drive circuit efficiency is, at present, more important (See Section 3.6.4.3).

An offsetting characteristic of the thin-film structure which reduces efficiency is the large capacitance per unit area. Multiplexing, especially line-at-a-time matrix addressing, leads to drive waveforms with high frequency components. The large capacitance in the structure results in high displacement currents which add to the power dissipation in the drive system (See Section 3.6.4). Some of the more significant electrical characteristics are shown in Fig. 3.6.6.

3.6.4 ADDRESSING/DRIVING

3.6.4.1 Approaches

The ZnS:Mn EL film requires a large electric field to cause it to emit light. The electric field must be sufficient to cause filamentary conduction in the phosphor but not so high as to cause the encapsulating dielectrics to conduct. An ac field is necessary for sustained operation. Despite these requirements, the wave shape of the excitation signal is not usually critical. There are several ways to implement the required voltage drive:

- a) At present, the most expeditious method is to use x-y matrix addressing and powering from the crossed grid, i.e., edge leads in combination with MOS drivers. This however, leads to a low duty factor for each element and lowers the luminance.
- b) Another way is to use discrete transistors at each pixel. While offering 100% duty cycle, this method results in an extremely expensive and cumbersome display.

c) A third method is to integrate a thin-film transistor (TFT) at each pixel in an array using thin-film fabrication techniques. The advantages of this approach, and very significant, are that each pixel can be on with a 100% duty cycle and that resonant power supplies can be used to save the imaginary power and reduce the overall power consumption. The disadvantage of this latter approach is that, so far, the yield has been low due to the great number of process steps (approx. 11).

3.6.4.2 Matrix Addressing

The discrimination ratio (steepness of the luminance vs voltage curve) is 10^4 - 10^5 , high enough to allow multiplexing hundreds of lines in a matrix display by the simple crossed grid approach. This fact has allowed successful demonstration of both graphic and video displays using this technology. However, luminance is limited by the duty cycle. The matrix usually consists of line and column electrodes with each intersection of the electrodes defining one pixel of the display (See section 2.2.3). Figure 3.6.7 shows an electrical model for a matrix EL display. The line and column electrodes are modeled as distributed resistances between each pixel. Each pixel can be modeled as an ideal capacitor in parallel with a non-linear resistor. The capacitance models the thin-film structure, and the non-linear resistor models the electrical effect of light being emitted by the EL phosphor. The effect of the non-linear resistor has a negligible impact on the entire circuit and is usually ignored for circuit analyses. Each pixel then, is represented by a single capacitance - C_p .

The image on an EL display is generated by programming the luminance of the individual pixels. The method associated with the programming of these pixels is commonly called the drive scheme, while the electronics needed to incorporate this drive scheme is the exerciser or generator. The exerciser electronics is divided into the logic and the high voltage drivers. The design of the logic is relatively straight forward with the vast source of microprocessors and integrated logic circuits available. The primary concerns for incorporating a drive scheme are the high voltage drivers and the interface of these drivers to the controller logic and the electrodes of the display.

There have been many drive schemes proposed for ac TFEL displays. All of them utilize the voltage luminance characteristics of the thin-film structure. Typical curves are shown in Figure 3.6.8. Most EL displays operate in a binary mode where a pixel is either on or off. Grey shading of the pixels can be done by operating at points along the voltage luminance curve.

A characteristic of the thin-film electroluminescent material is that it emits bursts of light, with each burst having an exponential persistence decay lasting about 3 m-sec (i.e., $L=e^{-t}$, with a decay to half brightness about 1.25 m-sec). Before a second burst of light can be activated, the ac TFEL material must be refreshed with a voltage pulse of the opposite polarity. Hence the drive of an ac TFEL display essentially requires an ac waveform. Also, because of this characteristic, the apparent luminance of the image on the display is dependent on the frequency at which each pixel emits the bursts of light.

The drive scheme pulses each pixel of the matrix display once per frame using a line-at-a-time addressing concept. By this means, the drive scheme steps through all the lines of the matrix display one at a time. For each selected line, the drive scheme lights each desired pixel along that line to the proper luminance and prevents all the other pixels in the display from lighting. The luminance of each pixel along the selected line is controlled through the corresponding column. Because of the matrix design of the EL display, all pixels are capacitatively linked; not only are the pixels along the selected line charged to a desired voltage, but all the pixels are charged to some degree. When these non-selected pixels are charged to a sufficient level to emit light, this is described as crosstalk. Eliminating this crosstalk is a principal requirement for the drive scheme.

To understand how a drive scheme eliminates crosstalk and achieves the desired image on the display, the network of capacitors representing the display can be simplified. Because of the line-at-a-time addressing and the binary operation of the pixels, the drive scheme interface to the display can be modeled as four leads. These are the selected lines, the non-selected lines, the selected columns, and the non-selected columns. The selected columns are defined by the columns corresponding to the pixels along the selected lines that are turned on. Likewise the non-selected columns are defined by the columns corresponding to the pixels along the selected line that are off.

Figure 3.6.9 shows the capacitive model for an ac TFEL display. N is the number of lines, M is the number of columns, and m is the number of lit pixels for the selected line. As shown, there are m pixels between the selected columns and the selected line and $M-m$ pixels between the non-selected columns and the selected line. The pixel capacitances for the remainder of the display are lumped into two model capacitances. With the capacitive model, drive schemes can be analyzed and drive electronics optimized.

3.6.4.3 Drivers

Although line drivers have been made from available discrete components, they are expensive and bulky. Several high-voltage MOS electronic techniques developed recently may lead to low-cost line and column drivers for EL displays. One such MOS approach is "Diffusive Self-Aligned MOS (DSA-MOS)", a form of DMOS. A second MOS technique uses VMOS (3.6.28). Both N/MOS and P/MOS can be made by the VMOS process, which can be combined to form a "push-pull" amplifier for ac drive. The "push-pull" driver is a distinct advantage over the type of driver available from DSA-MOS. Drivers are now being developed which should reduce the line power consumption by a factor of 2, initially, and 5 or more, subsequently. Miller and Tuttle (3.6.29) have reported on resonant drive circuitry which, theoretically, can reduce the real power dissipation to less than 10% of the power now used. This, or the successful achievement of TFT or similar drive techniques which allow 100% duty cycle and low power with resonant drive, will make a major impact on the utilization of TFELs.

3.6.5 SYSTEM INTERFACE

Although the ac TFEL is digital in nature, one current approach to the implementation of ac TFELs is to consider the display simply as a display monitor, i.e., the signal input would be compatible with, for example, a U.S. standard television RS-170 or RS-232 composite video input; all conventional signal formatting, symbol generation, and conditioning, etc., to be handled externally to the display monitor. The display monitor will provide the proper decoding (timing, x and y sync strip-off, etc.) to match to the internal refresh and matrix addressing necessary for the display, itself. In this manner, the display monitor can be used as a direct replacement for a CRT. The other system interface considerations appropriate to the CRT as enunciated in Section 3.1 generally hold for the ac TFEL display monitor. Both low and high resolution graphic and video signals would be processed in terms of the actual display characteristics.

3.6.6 VISUAL CHARACTERISTICS

3.6.6.1 Reflectivity

Specular reflectivity associated with a front glass surface is essentially independent of the technology. The now standard treatment is to use a high efficiency reflection reducing coating, such as that described in U.S. specification MIL-C-14806. Since the front surface of the EL display is glass, the same coating requirements would prevail.

In general, for an excited TFEL element to be directly visible against its background, the reflection of ambient light must be minimized. Most conventional emitting display schemes employ filters to reduce the internal specular and diffuse reflectance. This, in turn, also interferes with the emission from the display by introducing optical attenuation. The high contrast dark field TFEL requires no filters, thus all the light emitted forward from the TFEL layer is transmitted without attenuation. Because of the high index of refraction the ZnS layer, about 2.3, only a small cone with an angle of rotation of about 18 degrees is not totally reflected.

3.6.6.2 Contrast

With a vacuum deposited thin-film phosphor structure, ambient light is effectively scattered, i.e., diffusely reflected, only at the rear surface of the phosphor, in the region designated by dielectric film #2 (See Figure 3.6.2). Ambient light arriving through the display structure can be absorbed here, if dielectric film #2 matches the index of refraction of the TFEL film and is opaque. Taking advantage of this situation, high contrast display structures with a diffuse reflectivity less than 1/4 of 1 percent (3.6.30 & 31) were achieved. More recently, black layers measuring between 0.1 and 0.14% reflectivity have been demonstrated (3.6.32). Because very high contrast ratios can be obtained with a black layer, TFELs are readable in sunlight levels beyond 10^5 lux. As a specific example, a black layer TFEL display having a diffuse reflectance of 0.1% would reflect a 3.2 cd m^{-2} in a 10^5 lux ambient. If the display element (pixel), itself, emitted about 6.4 cd m^{-2} the contrast ratio would be the 6.4 emitted, plus the 3.2 reflected, divided by the 3.2 reflected off the black layer or $(6.4 + 3.2)/3.2 = 3$. Obviously, higher outputs will provide more than adequate contrast.

Thin-film EL alphanumeric have been demonstrated as more legible than comparable dot matrix CRT formats because of the sharp, square-dot pattern, though this has not been extensively tested (3.6.32). The practical grey scale range currently depends on the number of lines multiplexed and the ambient illumination. The inherent nonlinearity and the peak luminance does allow refresh matrix operation up to 500 lines with about $10\text{--}15 \text{ cd m}^{-2}$ luminance and negligible loss of contrast due to crosstalk. However, if a display is a large area, the peak currents will be large, and beyond 30 cm square, one must look more closely at the properties of the transparent electrode material to avoid waveform distortion in the interior of the panel. If the TFT approach or an equivalent process proves successful, not only would this problem be obviated, but luminance levels of up to 200 cd m^{-2} could be easily obtained.

3.6.6.3 Flicker

Flicker is easily detectable when a TFEL pixel is refreshed at below 50 Hz, although flicker or "strobing" can also occur under high vibration at higher refresh frequencies. The persistence of the phosphor is relatively independent of the current. Normally operated ac TFELs otherwise exhibit no flicker.

3.6.6.4 Resolution

Resolution, once a serious problem, is no longer a limiting factor. A panel with a density of 200 lines per cm across a linear dimension of 2.54 cm has been demonstrated (3.6.33) for use in a helmet-mounted display as well as a 512 by 640 line display at a density of 40 pixels per cm (100 pixels per inch) (3.6.34). The latter would appear to satisfy most graphics and video requirements. Line and column drivers are being developed to utilize the capability of these panels. The ultimate resolution is probably limited by the size of the pinhole destruction phenomenon (3.6.35).

3.6.6.5 Color

Work on color has not been extensive. Soxman et al, made a number of samples yielding green, yellow, orange and red (3.6.36). Probably because of other deposition problems, these samples demonstrated low luminance, efficiency and life. More recently, other work has been reported with better results (3.6.37 thru 39). For example, Hale reported a green output of over 300 cd m^{-2} (3.6.37). Work in color was also reported by Chen (3.6.40). Examples of colors achieved by using rare earth activators are: white (PrF_3); blue/green, yellow, and red (DyF_3); blue (TbF_3), Green (TbF_3), blue (E^3F_3) and red (E^2F_3).

At the present time, the only color which is produced with good efficiency in thin-film EL devices is the yellow with a wavelength spectrum of light emission approximately 50 nm wide at half luminance and centered at about 585 nm at about 5 lumens per watt. While other colors can be produced by ZnS with rare earth dopants, the best, so far (green), has yielded an efficiency of less than 0.5 lumen per watt. This is a drawback which may have some fundamental basis in the nature of rare earth electron configurations in ZnS. Further studies are expected to shed more information on this matter. Like the manganese, the emission is relatively independent of temperature and frequency. This is a very important consideration for matrix addressed displays operating over a wide temperature range such as for military applications, particularly since many frequency components are present in matrix addressed systems.

3.6.6.6 Viewing Angle

Viewing angle, often a critical factor, such as in liquid crystal displays, is not a concern with TFELs. The image can be seen almost to ± 90 degrees although the practical limit for alphanumerics and complex graphics is probably only useful to about ± 70 degrees.

3.6.7 OTHER EL DEVICES

3.6.7.1 AC Powder EL

AC Powder EL is the historical variety associated with Destriau, the object of an enormous research effort in the 1950's and early 1960's aimed (unsuccessfully) at making it an efficient source of illumination, and well described in a book by Ivey (3.6.41). The active layer, which consists of a suitably doped ZnS powder (5-20 μ m grains) suspended in a dielectric, is sandwiched between two electrodes, one of which is transparent, and is supported by a substrate. The substrate may be glass, flexible plastic, or may be a metal such as aluminum. In the latter case, the top electrode must be transparent. The dielectric may be organic (e.g. cyanoethyl cellulose) or a low melting point glass. A second dielectric is often used as extra protection against catastrophic dielectric breakdown. Applied fields of 10^4 - 10^5 V cm⁻¹ are sufficient to produce luminance as high as 340 cd m⁻² at efficiencies which are reasonable by display standards (1-5 lumens per watt). Luminance increases with frequency at moderate frequencies (100- 10^4 Hz), but device life is usually decreased in the same proportion. One has a choice of colors depending upon the activation of the ZnS powder. Copper is always used in these EL powders. The combination of Cu and Cl can give either blue (460 nm) or green (\approx 510 nm) emission, depending upon the relative amount of Cl, while the combination Cu, Cl and Mn yields yellow (\approx 585 nm).

Empirically, a key parameter is particle size, which is involved in some critical tradeoffs. Small particle size increases efficiency and nonlinearity, but decreases life. Efficiency generally has the functional form $L^{1/2}V^2$ (where L is luminance) and usually peaks well below the highest luminance levels; this ultimately relates back to particle size which is increased to improve life, yet decreased to improve luminance, nonlinearity and efficiency.

Much of the behavior can be understood if one looks at the microscopic nature of the Destriau phenomenon. The best synthesis of observations and ideas on this subject is the work of Fischer (3.6.42). EL powders are typically fired at high temperatures where the

hexagonal phase predominates. When they are cooled, there is a transformation to a cubic zinc-blend structure, and the copper (previously mentioned as essential), which exceeds the solubility limit, precipitates on defects resulting from the hexagonal to cubic transformation. The result is imbedded Cu_xS conducting needles which act to concentrate an applied electric field at their tips. Thus an applied field of 10^4 - 10^5 V cm^{-1} can induce a local field of 10^6 V cm^{-1} or more. This is enough to induce tunneling of holes from one end of the needle and electrons from the other. The holes are trapped on Cu recombination centers, and upon reversal of the fields the emitted electrons recombine with the trapped holes to produce light. Larger particle sizes lead to longer needles and greater field enhancement, but as the shunted material still contributes to the losses, efficiency is reduced. In addition, the localized current flow results in localized heating. This, together with the high fields, can result in diffusion and electromigration of active species such as Cu^{+2} or harmful sulfur vacancies which interfere with the emission process. The Lehmann (3.6.43) hypermaintenance process was, in fact, an attempt to reduce and control sulfur vacancies, which also affect the mobility of Cu ions. Since moisture is thought to be a source of sulfur vacancies at the particle surfaces, Fischer et al (3.6.44) proposed that phosphor particles should be microencapsulated with a phosphosilicate, after Lehmann-type processing, to yield even longer life. The longer life associated with larger particle diameter is related to a longer diffusion time for defects generated at the surface of the grains. Life is still a key problem for the application of this technology, but there is indeed some expectation for more than 10,000 hour life at moderate luminance, especially for green-emitting devices. The problem is that peak luminance is a serious limitation, and low duty cycle operation is not acceptable. This is especially important because the powder reflects ambient light, and good contrast is achieved by the use of an absorbing filter on the front of the display, as in a CRT display. These absorbing filters, however, seriously reduce the emitted light.

The most promising approach to using ac powder EL in complex displays is in conjunction with arrays of thin film transistor (TFT) circuits. Several groups pursued this approach (3.6.45-47) with the most impressive results obtained by Brody et al (3.6.45). Currently, ac powder ELs are used in some civil aircraft control panels for night illumination and are being tested for use in military aircraft as well, particularly because of the need for compatibility with night vision goggles. These displays, however, cannot satisfy the high luminance aircraft environment.

3.6.7.2 DC Powder EL

There is another type of powder EL device which is associated primarily with A. Vecht and his collaborators (3.6.48 & 49). In the ac powder case, the high temperature firing and cooling results in a conducting Cu_xS surface layer on the particles, which is removed chemically. In the dc powder case, a fine grain ($0.5\text{--}1\text{ }\mu\text{m}$) Mn-doped ZnS powder is prepared with Cu_xS coating, and a layer of the powder (with a small amount of binder) is formed into the device. If a matrix display is being fabricated, the powder layer, which is $40\text{--}50\text{ }\mu\text{m}$ thick and is conducting, must be patterned into strips so that there is no shorting from line to line. Such a device must be "formed". When a voltage is first applied, a large current flows, the layer heats up, and gradually a narrow region about $1\text{ }\mu\text{m}$ thick, adjacent to the SnO_2 anode, begins to luminesce. In the standard ZnS:Mn device, the light is yellow (585 nm), characteristic of Mn emission in ZnS.

There are three points to be made regarding this structure. First, the general requirement that the thick powder layer be patterned, limits the resolution which one can easily achieve relative to thin-film structures and even relative to ac powder structures. Second, this structure, by itself, provides no protection for the phosphor powder; thus it must be hermetically sealed. Since one is dealing with a white powder device viewed through the glass substrate, good contrast in high ambient illumination is at the expense of device luminance, i.e., system efficiency. One valuable characteristic of dc powder devices is that they can be operated in a pulse mode beyond the voltage and luminance of the forming condition, and the net effect is a better discrimination ratio and average luminance than one might have expected from the dc characteristic (3.6.50).

Luminance maintenance seems to be a somewhat complex question for these devices. There is no simple functional form for the decay; although pulsed operation, in particular, and low luminance operation, in general, lead to longer life. Devices operated at 8 cd m^{-2} (pulsed) can be expected to retain more than half their initial luminance for more than 10,000 hours in the best cases. Recently, Alder et al, (3.6.51) reported good quality panels with mean luminance values of between 175 and 350 cd m^{-2} and a half-life luminance of 3000 hours.

An interesting application of dc powder is the alphanumeric matrix display development first reported by Mears et al (3.6.50), taking advantage of the unique pulse response characteristics. While the initial report described a 36 character display, they also discussed the capability for increasing the size to a 200 line display of 1250 characters, which they subsequently achieved (3.6.52). Other mechanizations and interface electronics were discussed by Smith and Werring (3.6.53)

Much of the recent work in this technology has been aimed at extending the available color range by using different powder materials and different activators. DC electroluminescence has been demonstrated for various rare earths in ZnS and for Mn in Ba_2ZnS_3 (3.6.54) as well as for a number of alkaline earth sulfides doped with rare earths (3.6.55 & 56). Most of these alternatives have been much less efficient than ZnS:Mn, Cu, but recent results are encouraging; for example, ZnCaS:Ag produces green (70:30) and red (30:70) emissions which are almost one third as efficient as the standard yellow phosphor. There is also a fairly good blue-green (SrS:Ce, Cl) phosphor. Most important is the steady rate of progress in these new EL materials, which may stimulate renewed interest in this technology, especially where a range of colors is important. DC powder ELs are being used in several applications where the luminance environment is controlled. However, as in the case with the ac powders, these displays will not meet the high illumination aircraft environment.

3.6.7.3 DC Thin Film EL

The simplest electroluminescent structure one can conceive of is a thin-film of phosphor with electrodes on both sides driven by a dc source. This is probably the reason why the intuitive urge to exploit the phenomenon had so often led people in this direction. Attempts to make devices of this sort go back many years, and the materials most often used are the familiar ones, ZnS:Mn, ZnS:Cu,Cl, and ZnS:Mn,Cu (3.6.57-61). The basic problem with thin-film devices excited by dc voltages has been a tendency toward catastrophic failure, especially in the case of films without copper. For devices employing ZnS:Cu,Mn, there is at least one layer of Cu_xS adjacent to the phosphor film. It appears that in the absence of copper, or for low concentrations of copper, the fields required to initiate luminescence are so high that avalanching takes place, leading to negative resistance and a runaway current. A resistive layer stabilizes the current distribution. When Cu_xS is present, not only can lower fields be used, but very likely, the recombination of Cu sites suppresses space charge formation and negative resistance effects. (Films, with copper, can, under ac excitation, behave analogously to ac powders (3.6.62) and probably involve alternate injection of holes and electrons from Cu_xS .)

A variety of luminance-voltage dependencies have been reported for dc thin-film devices, but the common characteristic is a greater nonlinearity than is typical for ac powders. The most interesting recent work in the ac film area has been that of Abdalla and Thomas (3.6.63). This device seems to be a direct film analog of the dc powder device of Vecht et al (3.6.49), with a Cu_xS injecting layer and a copper-free active layer being created during the forming process. As with dc powder devices, it works best in the pulse mode, which apparently allows the high fields necessary for impact excitation of manganese without excessive heating. Under these condition, they reported good maintenance.

Further performance data was provided by Abdalla et al, at the 1980 IEEE-SID-AGED Biennial Display Conference (3.6.64 & 3.6.65). Similar structures were reported by Vlasenko and Gergell (3.6.66), but no indication of device life was given. Finally, there are reports of dc electroluminescence of reasonable efficiency in films of other materials, such as CdF_2 , and La_2O_3 , but neither of these appears to be suitable for practical use at this stage; CdF_2 films are not sufficiently stable, and La_2O_3 has low luminance output.

3.6.8 STATE OF DEVELOPMENT

It can be concluded that each of the four types of electroluminescent displays may find useful commercial and industrial application. Military applications, however, are more stringent. In the case of ac powder devices, if the applications are to go beyond the simple direct address displays (or lamps, as they are commonly called), it is important that good TFT arrays be developed. If that should occur, the ac powders may prove to be useful, albeit limited luminance. Ac powder devices have been proposed for night lighting in military vehicles where night-vision goggles are to be used. The dc powders now appear to have enough life to be useful and are being exploited for several applications in the U.K.; they have the drawback of all matrix displays - high drive cost, but like the ac powders could be used in limited airborne applications, such as for night lighting at low illumination levels. The principal advantage presently seems to be the variety of colors which can be provided. Dc films are also achievable; they can be driven with a relatively low voltage and used at room temperature. Nevertheless, considerably more development must take place before they will be competitive with the powders.

The ac thin film EL devices are still the most interesting for military airborne display applications because of their many attractive features: high peak luminance, long life, nonlinearity, contrast, memory, and currently, a high probability to provide several colors. Nevertheless, matrix displays will not find wide application without reduction in drive costs.

The following high-contrast ac TFEL devices represent a few devices being developed for military airborne application.

- a) A low cost, end buttable, seven-segment, two digit display, with drive electronics, mounted on a standard dual-in-line package (DIP).
- b) A 40 pixel cm^{-1} , 512×640 line, matrix display, capable of complex graphics and video, with rear mounted drive electronics, capable of at least 7 video levels at 10^5 lux ambient.
- c) A 13 pixel cm^{-1} , 16×29 line discrete, with rear mounted drive electronics, for use as a 10 alphanumeric character indicator or multi-legend display switch.

For military airborne applications, legibility in high ambient illumination is not a wish, but a requirement. As suggested at the beginning, ac thin-film EL devices show the greatest promise for exploitation, particularly in the case of direct view dynamic displays presenting vector graphics and video information. It would appear that production devices and compatible drive circuitry are at hand and may soon be available for integration into military airborne subsystems (See Chapt. 4)

The above mentioned 512 x 640 line display measures 13 x 16.25 cm. Theoretically, the size is limited by the size of the vacuum chamber; in practice, a 30 x 30 cm display, now in development, probably represents a practical limit. However, most aircraft applications could be satisfied by the present state of the art (approximately 20 x 20 cm.).

Not included under reliability is surviveability. Because the structure is basically solid-state, vibration and shock are not critical concerns. Since the substrate is a glass plate, the usual precautions for glass must be taken.

Finally, as indicated in 3.6.3.5 and 3.6.4.3, power dissipation is principally contributed by the drive system. Nevertheless, the estimated power requirement for the 512 x 640 display, including the drive system, is under 20 watts.

3.6.9..ACKNOWLEDGEMENTS

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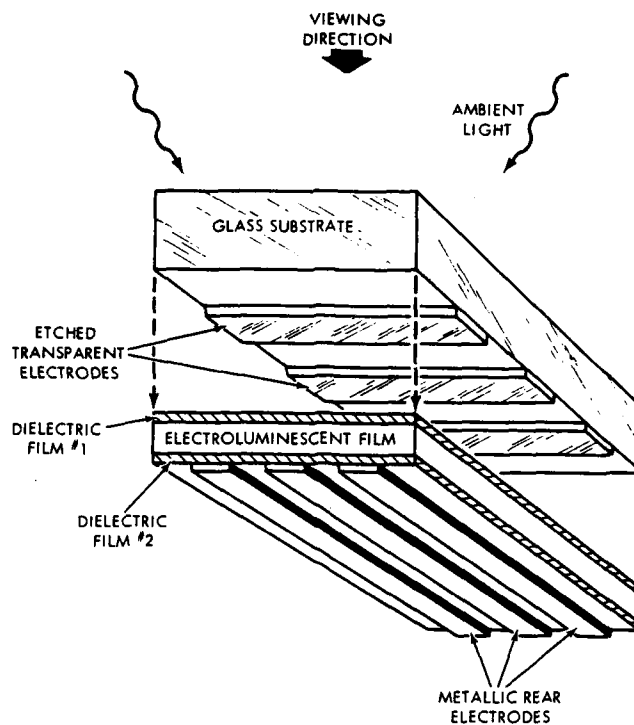


Fig.3.6.1 Schematic representation of a three layer, ac coupled ZnS:Mn thin-film device employing two transparent dielectric layers

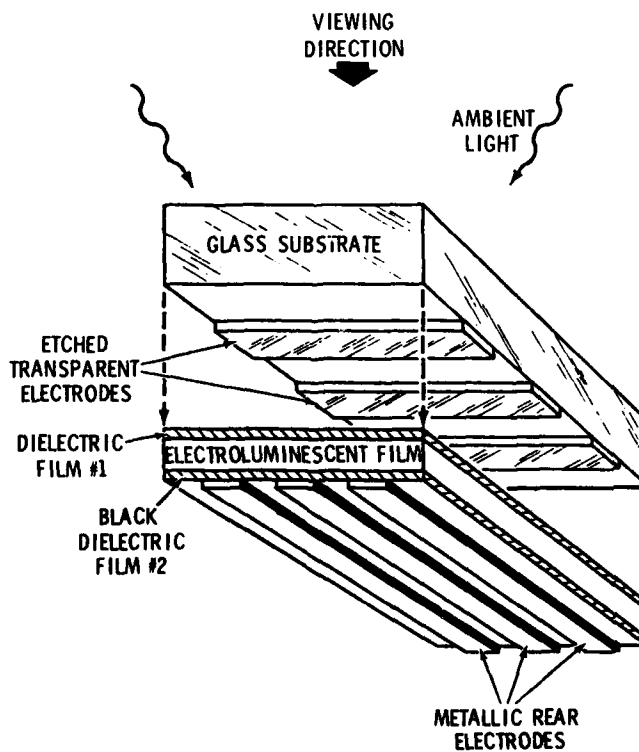


Fig.3.6.2 As Fig.3.6.1 but with a black light-absorbing rear dielectric film

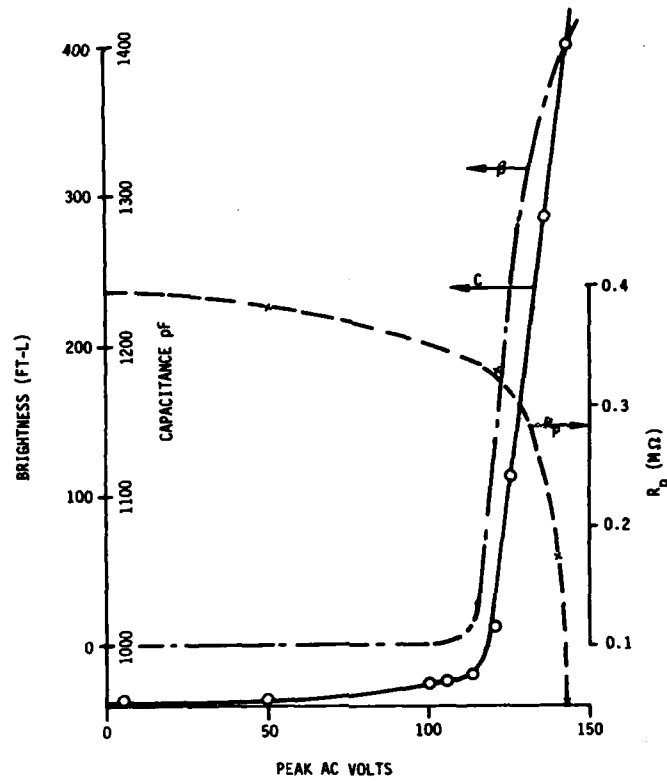


Fig.3.6.3 Typical luminance versus voltage curve showing the steep ac TFEL characteristic

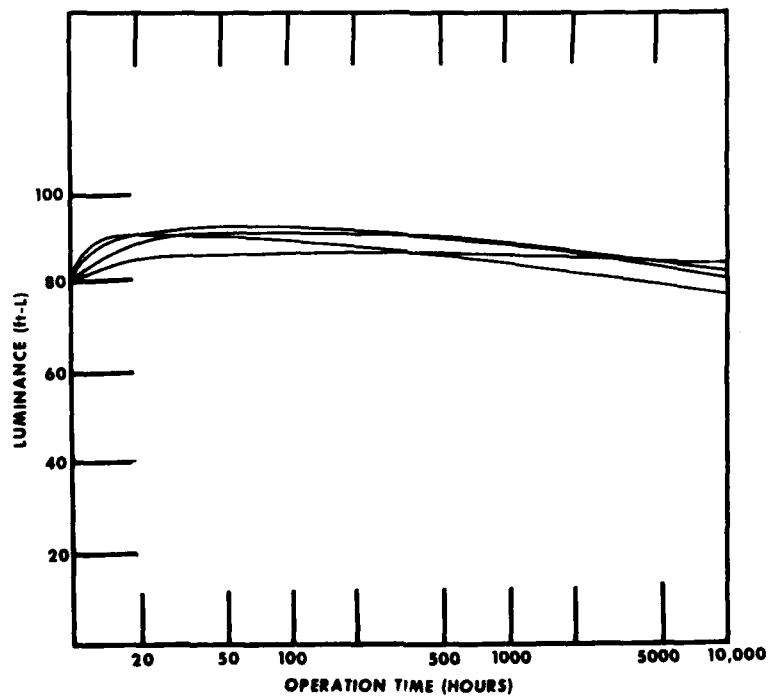


Fig.3.6.4 Improved luminance effect of burn-in of an ac TFEL resulting in a high maintenance profile

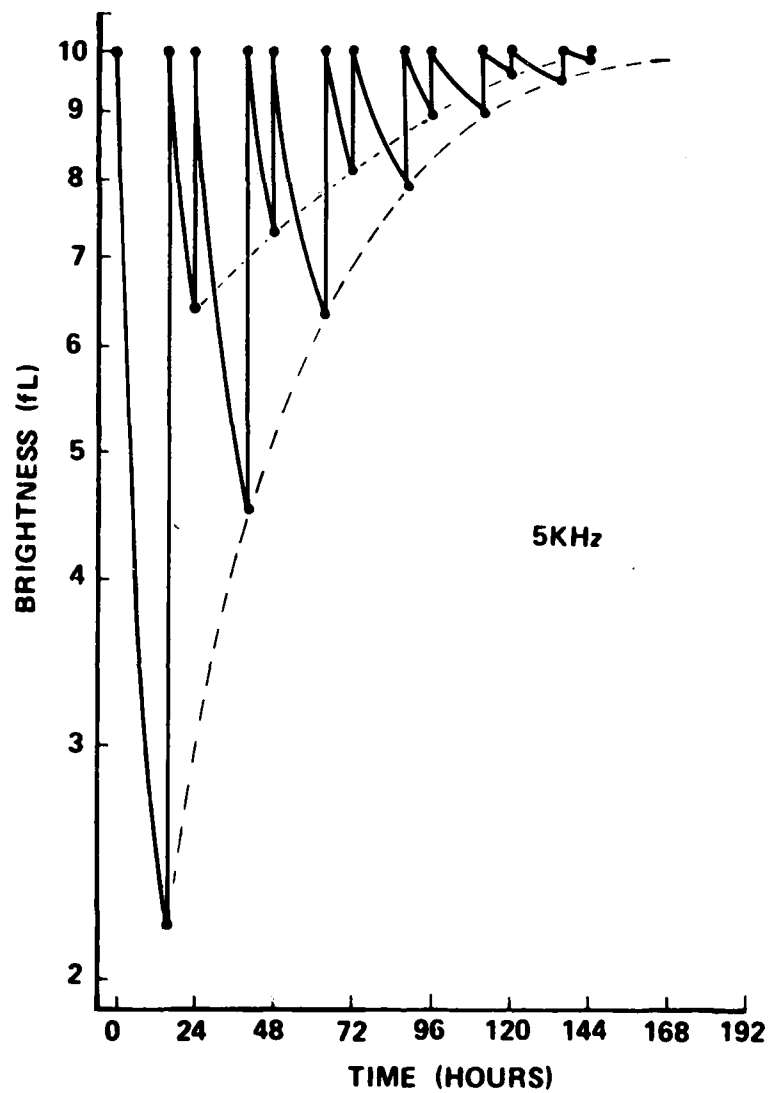


Fig.3.6.5 A short term typical flat maintenance curve resulting from periodic voltage adjustment

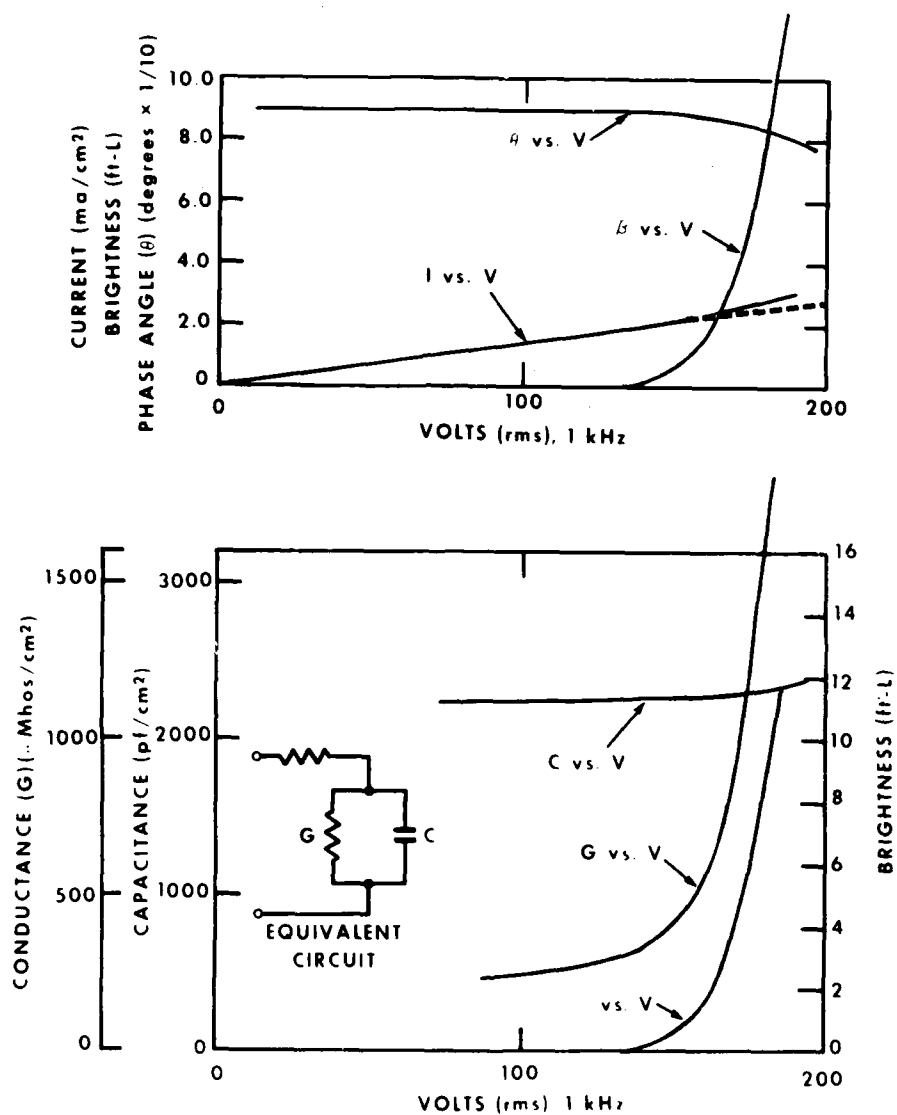


Fig.3.6.6 Electrical circuit characteristics of an ac TFEL display

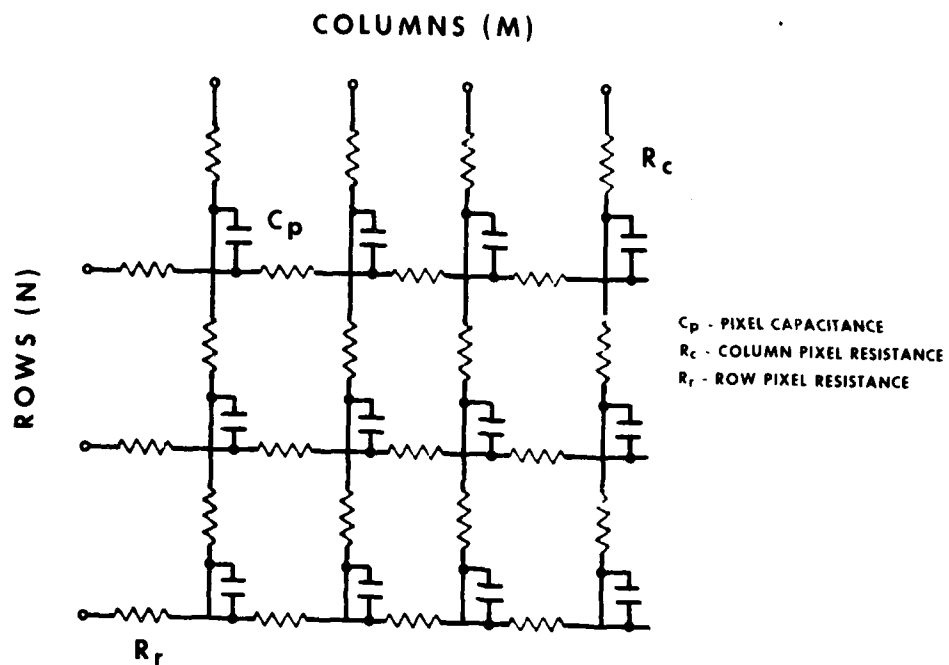


Fig.3.6.7 Electrical model of a matrix TFEL display

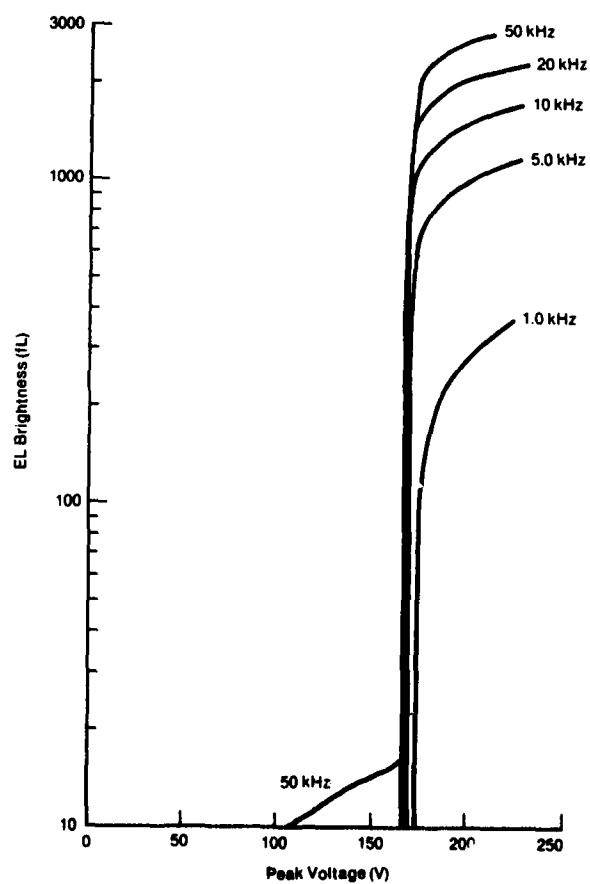
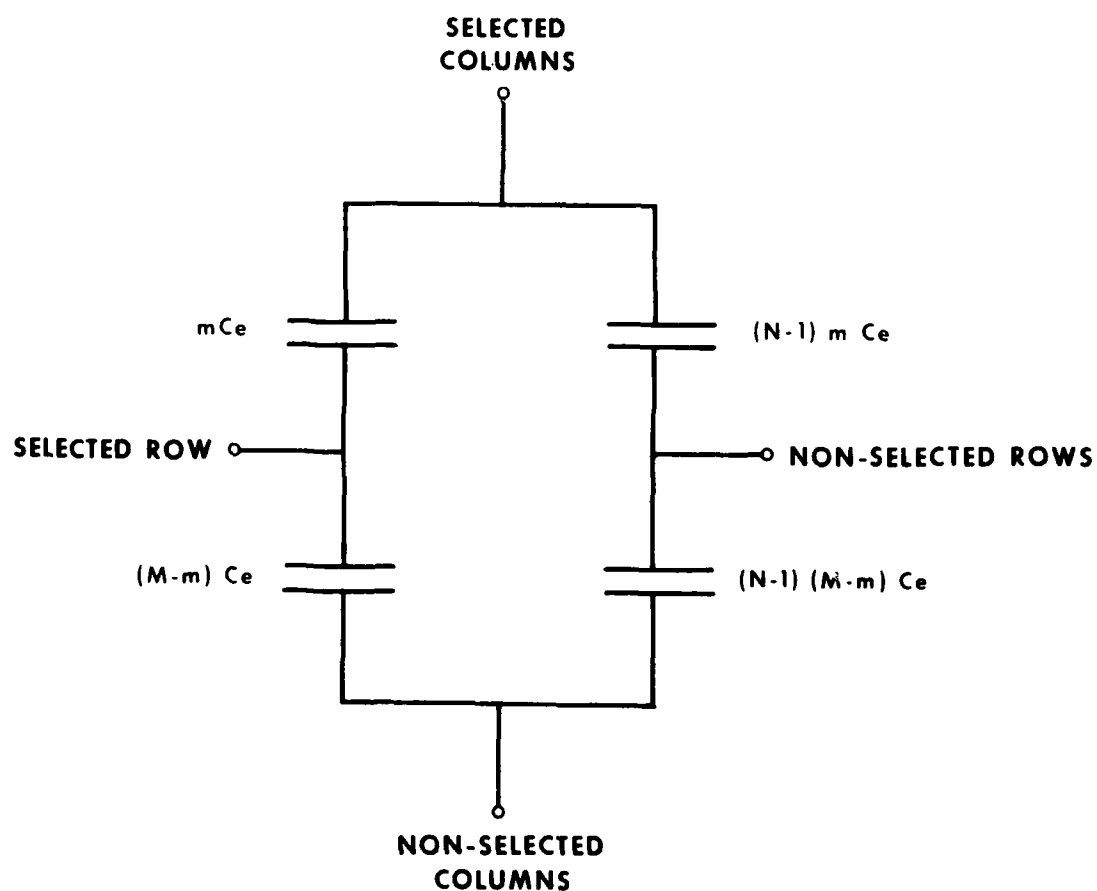


Fig.3.6.8 Typical steep luminance versus voltage curves



M - NUMBER OF COLUMNS
N - NUMBER OF ROWS
m - NUMBER OF SELECTED PIXELS PER SELECTED ROW
 C_e - PIXEL CAPACITANCE

Fig.3.6.9 Capacitive model of a matrix ac TFEL display

VACUUM FLUORESCENT TUBES

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1 HISTORICAL SURVEY

The vacuum-fluorescent tube was first proposed as a display device in 1967 (1), and its subsequent history is described in Ref. 2. The first generation of these displays mainly comprised individual tubes, each capable of displaying one 7-bar numeric, and these were extensively used in desk-top calculators. From 1971 onwards tubes became available capable of displaying up to twelve numerals within a single flat glass envelope, and in further improvements from 1974 onwards the construction was simplified by the replacement of ceramic anode substrates by glass substrates forming a part of the vacuum envelope. Subsequent developments have been concerned with improving the color characteristics and efficiency of the phosphor, with the use of thin film printing in the production process, and with the expansion of the number of elements in each display so that matrix displays of up to 250 x 250 elements are now available. The most recent advances are aimed at improving the luminance of large area displays by the use of active substrates ; this allows more rapid addressing, and compatibility with TV display formats.

2 PRINCIPLES OF OPERATION

Vacuum-fluorescent tubes form a type of display in which light is emitted from phosphor-coated anodes when these are subjected to electron bombardment, using the principle of cathodo-luminescence. As compared with cathode-ray tubes the electron energies are much lower, typically 50 eV, and the display pattern is formed of discrete anode elements rather than by a focussed beam striking one part of a continuous anode surface.

Fig. 1 shows a typical layout for a simple tube. Although diode operation is possible, tubes are usually constructed as triodes to allow easier control of luminance. The cathode is a thin oxide coated tungsten filament which is run at dull-red heat (600°C) and is therefore not normally visible, and the grid is a thin metallic mesh. The anode is normally formed of a pattern of thin-film electrodes deposited onto the top surface of the rear glass wall of the vacuum envelope, and on each of the electrode elements a further deposit of phosphor ($ZnO-Zn$) is laid down. This fixed pattern of anode/phosphor elements may be in the form of a series of 7-bar numerals, 5 x 7 dot-matrix patterns, or sometimes a series of bars forming thermometer-scale indicator. The simpler types have been described by Suzuki (3) and Sato (4), and a large display of 6x40 characters each formed of a 5 x 7 dot-matrix by Kasano et al (5).

The luminance of each dot or bar is controlled by a combination of the grid and anode voltages ; in practice it has been found desirable to operate the grid and anode at the same potential to avoid focussing problems, so the control of electron current and luminance in each area of phosphor is through simultaneous variation of grid and anode voltage; For the smaller matrix tubes the grid voltages of the individual pixels are operated in a time-multiple mode ; duty factors of 1/20 TO 1/50 are typical for these displays.

To address each pixel independently it is necessary to have a matrix of two sets of connections orthogonal to each other. The phosphor dots are then laid on the anode conductors and the grid wires are set at a right angle.

When a positive voltage is applied to both one anode conductor and one grid, the electrons are allowed to reach the phosphor which lights-up in turn. Some difficulties occur, though, with electron trajectories which result in non uniform illumination of anode dot due to the influence of neighboring negative grids. By splitting each anode

point (Fig. 2) into two parts (or even more) individually connected and shifting the grid structure by a half pitch this can be solved but at the expense of a limited resolution. To overcome this major limitation Narumi China (6) replaces the layered conventional anode structure by stripes on which the phosphor is directly deposited (fig.3), these stripes are at a distance from the rear wall. The "through holes" conduction and lateral insulation problems are thus solved. An additional "digit forwarding" set of grids may be added for multiplexing and reduce the number of drivers.

Based on the same principle, Ge of the Hangzhou University recently described (7) multi-grid (tetrode and pentode) structure panels operating at TV frequency and displaying over one hundred thousand pixels. Previously Uemura and Kiyozumi (8) had described an experimental vacuum-fluorescent TV display in the form of a 241 x 246 element array with full addressing flexibility at TV frequencies. To isolate the tube pixels from the address circuits, it incorporates active elements on a silicon substrate but the display is thus constrained to the substrate size of 23 x 23 mm². For these TV displays the loss of luminance resulting from time-multiplexing is obviated by use of capacitances at the individual anodes which maintain current throughout the duty cycle.

3 PHYSICAL CHARACTERISTICS

A typical simple tube consists of a flat-walled glass envelope as shown in Fig. 1. The dimensions of the rectangular flat front and back are determined by the particular array of numerals or the matrix size and shape, and also by the application which may be for a series of small numerals on a pocket calculator, or may be much larger as on consumer products such as clocks, washing machines, etc... Character sizes range from 5 mm to 15 mm in height, and overall display sizes from 20 mm x 50 mm to 140mm x 270 mm. The Ge TV panels have a useful area of 134 x 182 mm. Typical display thickness is in the range 10 mm to 14 mm.

The matrix TV display described in (8) has 241 x 246 picture elements and a picture size of 23 mm x 23 mm. This is clearly too small for most practical applications, and to fabricate a direct-view display it would be necessary to mount several silicon substrates together to form a single continuous display. It is indicated in the paper that such a joining process may be possible.

The smaller display devices are very rugged and can withstand a broad range of environmental conditions; they are therefore suitable for a wide range of industrial and consumer applications, and using well-established vacuum-tube technology there are few difficulties in their production. The production process was greatly simplified and reliability improved in 1974 when thick-film printing techniques on a glass substrate were utilised to replace ceramic substrates, and allowed a greater variety of display patterns to be produced. An example of this is provided by the 240 character display described in Ref.5 (Fig.4) in which to improve production yield and reliability it was decided to minimise the number of electrical overlapping points in the anode-matrix wiring array. Ref. 5 describes the production process which produced a 3-layer anode substrate having only two overlapping points per dot. Ref. 6 describes the manufacturing process for the experimental TV display on silicon.

4 ADDRESSING/DRIVING AND SYSTEM INTERFACE

Except for very simple single-numeral displays, individual dots or bars are excited by time-multiplexing. Ref. 5 describes the method used for a 240 character display, each character being formed by a 7 x 5 dot matrix plus a cursor. Since then a 12 rows of 40 characters display has been introduced; this is the most complex display which is commercially available but the addressing technique used on simpler displays is similar in principle.

The 240 characters are divided into six rows of 40 characters, with 40 grids, each covering a column of six characters. The anodes for each column have 216 individually connected dots (six characters x 26 dots). Complete freedom for addressing individual dots is provided by time-multiplexing the voltages on the 40 grids; allowing for a blanking time of about 50 microsec. between grid pulses a duty cycle or 1/45 is obtainable when the complete cycle is repeated at 50 Hz.

A microprocessor is used for the addressing system. The CPU executes control of driving circuits and I/O data, and the driving program and all character patterns are stored in ROM. A shift-register is used to assemble a column of six characters before these are input to the drivers, allowing the pattern for one column to be built up while the previous column is being excited. Anode and grid voltages have a maximum value of 50 V (in that case, but over 75 V pulsed may be necessary as for the 256 x 256 dots Narumi panel where the multiplexing factor is 260) the luminance of the display being reasonably linear with voltage. Anode and grid currents per column are in the 0-30 mA range, so that the driver circuit requirements are compatible with IC characteristics. A single IC package incorporating shift registers, latches and drivers is also described.

The electrical field that is applied between anodes and cathode would be non uniform in the case of extended length filament connected to a d c source. This would result in luminance non uniformity along the line. Therefore heater voltage is generally limited to a few volts and supplied in the form of a c with a center tap transformer. However for larger displays with a high multiplexing factor the frequency must be high with respect to dot addressing time so that the cathode potential might be considered as being its average value during that time (for instance 7.6 volts and 0.625 mA rms at 20 kHz for the 12 rows of 40 characters of ISE where the useful length of the display is 150 mm). In the case of the Ge TV panel, it must even be pulse heated and the video signal applied during its cooling down to maintain contrast and grey shades capability. In the latter, in order to simplify the anode drive circuitry, the anode strips are divided into N/P groups (N total number of strips, P number of strips per group) the corresponding strips of each group being tied together. Similarly the first grid is divided in such groups. The total number of connexion can be reduced from N to $(2N)^{1/2}$. Several grid driving methods have been tested to eliminate cross-talk while keeping a good resolution.

The Uemura (8) TV matrix display uses a MOSFET array formed on the silicon substrate to isolate the pixels from the matrix addressing array. Each pixel has a phosphor anode which, as shown in Fig. 5, is deposited as a layer on the drain of a p-channel-type MOSFET transistor. The picture element is selected for energising by the applied voltages on the gate and source, which are matrix-addressed, and a potential corresponding to the source voltage is produced at the phosphor layer. By building in capacitance between the drain electrode and the silicon substrate the voltage on the phosphor decays slowly when the applied matrix voltages are cut off, so reducing the luminance, reduction which is otherwise inherent in matrix addressing. Ref. 2 mentions that studies are in progress on the application of TFT substrates to vacuum-fluorescent tubes; these would similarly allow higher brightness to be achieved.

5. VISUAL CHARACTERISTICS

The patterns of figures or lines which can be displayed are defined by the shapes of the phosphor layer printed onto the anode, and more particularly by the 7 x 5 dot matrix blocks or 7-bar numerals which are similar to those used in LCDs such as LCs and LEDs.

The principal visual characteristics of the display are determined by the phosphor and the cathode. The phosphor used is a green phosphor which has a broad-band emission spectrum with a peak wavelength of about 520 nm.

A range of individual colors from blue to orange can be obtained by using suitable filters. However, the use of filters decreases the perceived luminance which typically has a maximum of 700 cd m^{-2} when unfiltered, but only $200\text{--}300 \text{ cd m}^{-2}$ if filtered to produce a green color. The use of filters does improve contrast by reducing the level of light scattered back from the interior surfaces of the display; the worst effect of this scattered light is caused by the printed phosphor patterns on the anodes, the grids and the individual conducting leads to the anodes which all contribute to a fixed pattern which is very apparent in bright ambient illumination. The use of narrow-band filters as in some CRT displays to minimise ambient light scattering is not feasible with vacuum-fluorescent tubes because of the broad-band emission from the zinc oxide phosphor. The resolution of VFDs is rather coarse mainly due to the anode structure ("through holes") and in most instances pixels pitch is in the range $0,6\text{--}1\text{mm}$. The best value mentioned is $0,32 \text{ mm}$ pitch and $0,22 \text{ mm}$ dot size.

Alternative phosphors of different colors are being developed, but it appears that at the low voltages used in this type of display their luminous efficiency is likely to remain less than 5 lm/W . Among those which herald the "fourth generation" of VFD, capable of multicolor display are ZnS:Cu:Al (green light); ZnS:Cu:Au (lemon yellow); ZnS:Mn (yellow orange); Zn-Cd:S:Ag (red); ZnS:Ag (blue).

6. STATE OF DEVELOPMENT

The alpha-numeric and segment vacuum-fluorescent tubes are in large-scale production for a range of display applications including calculators, radio and communication equipment, clocks and other domestic and industrial appliances. The development of the 480 characters and 128×128 dot matrix displays indicates that further market penetration into computer terminals and word processors may be possible. However, the use of separate filament cathodes and grids may limit the extent to which large matrix displays can be realised as production devices.

Excellent reliability, life and environmental characteristics are claimed for the smaller types, and production cost is generally relatively low. For these reasons the display is potentially attractive to the automobile market, although the difficulties of viewing the display in bright ambient conditions may limit this application. Ref. 8, in describing the experimental work associated with the TV matrix display, quotes luminance levels of around 15000 cd m^{-2} for individual pixels fabricated with transistors and capacitors and operated at TV refresh frequencies. If such values can be achieved with representative displays should be capable of widespread use in aircraft cockpits, but thermal problems inherent in such a display will be very difficult to solve, and it is likely that much further work will be necessary to achieve these high levels of luminance in production displays.

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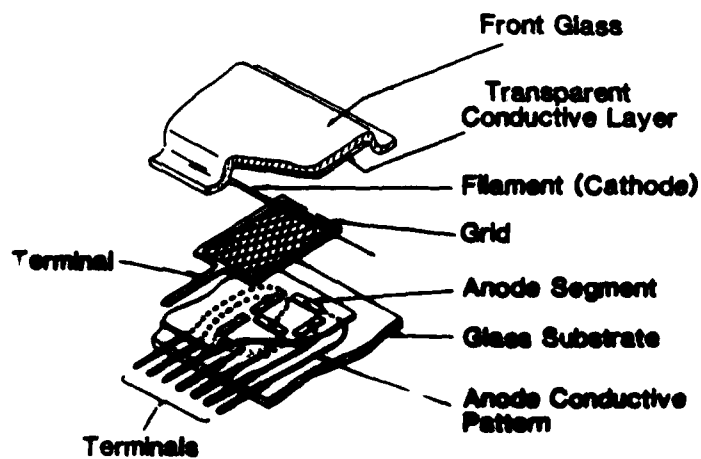


Fig.1 Layout of a conventional VFD

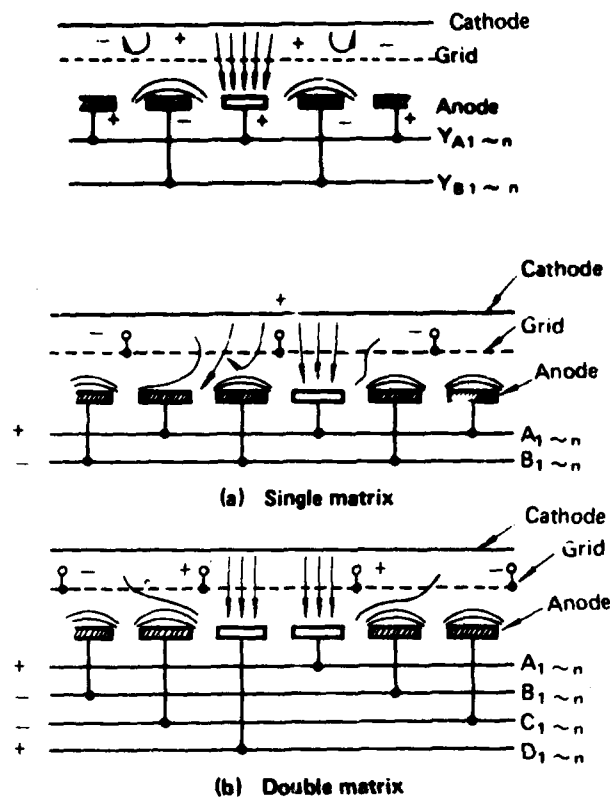


Fig.2 Anode splitting

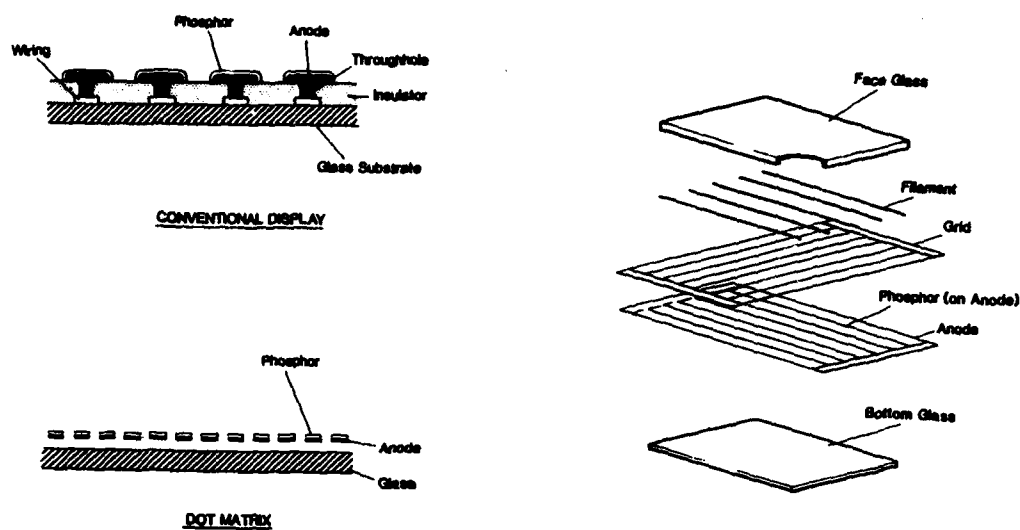


Fig. 3 Conventional and Dot Matrix Display Structures

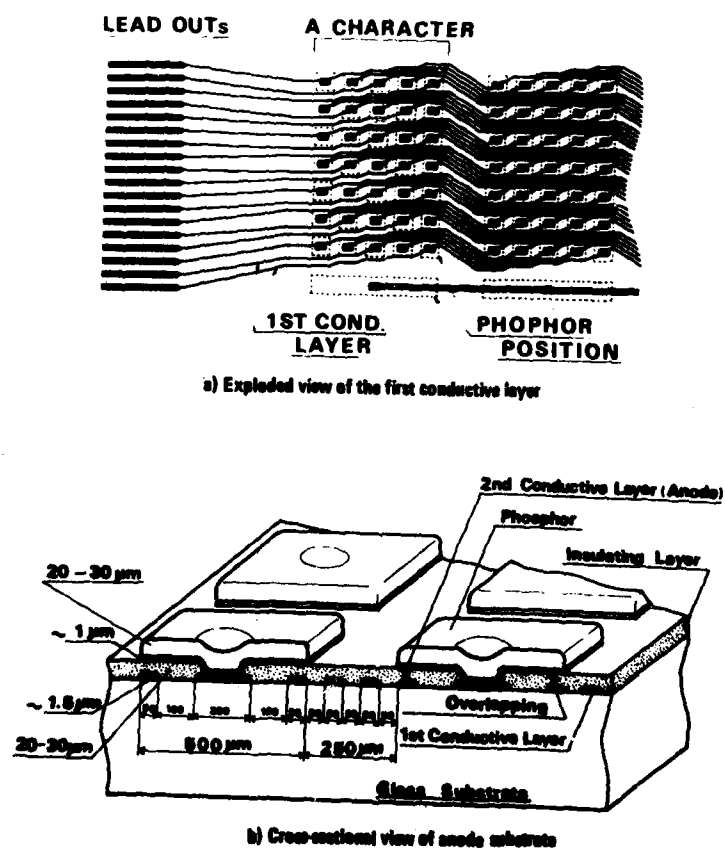


Fig. 4 6 x 40 Dot Matrix Display

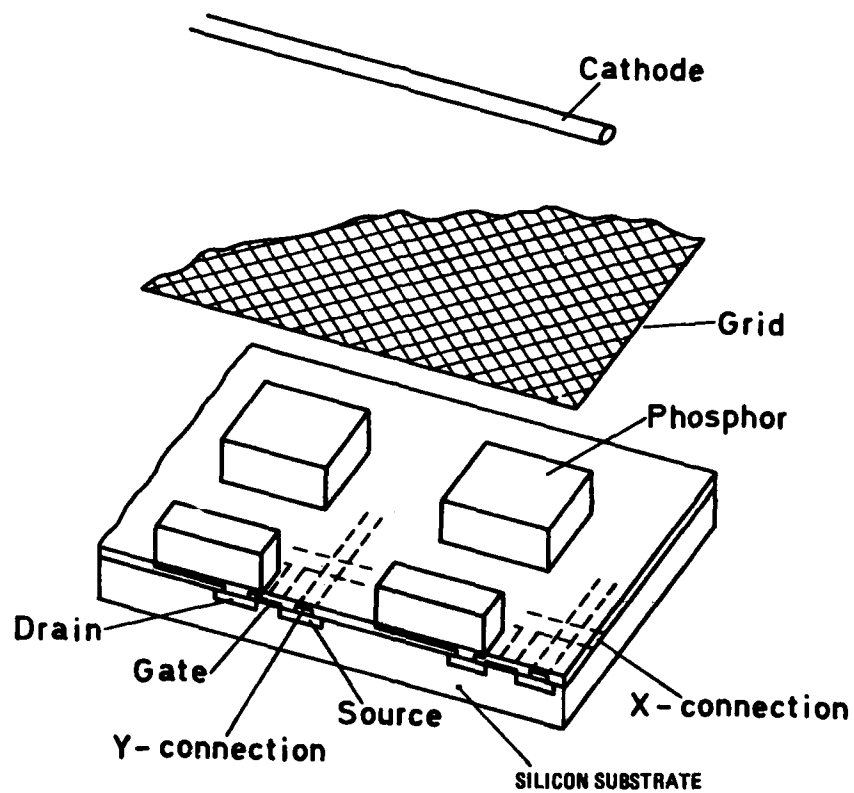


Fig.5 TV matrix VFD on silicon

LARGE AREA GAS DISCHARGE DISPLAYS OR PLASMA DISPLAYS

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1 HISTORICAL SURVEY

Undoubtedly the oldest electro-optical phenomenon able to produce light is an electrical discharge in a gas. Although this phenomenon is at the present time supposed to be at the origin of life on earth, millions of years elapsed until this effect was identified, analyzed and mastered by man. The "Paschen law" describing the discharge relationship (for a given applied voltage between two electrodes, the product of their distance multiplied by the gas pressure is a constant) dates only from the end of the 19th century (1889).

It is only in the early fifties that Kuchinsky developed a numeric indicator tube which became a standard for readout devices under the name of NIXIE. More recently, in the late 60's, other techniques began to replace it. In the NIXIE tube a single anode and a stack of separate cathodes, shaped in the form of numerals, are immersed in a gas mixture (1).

First attempts to produce a matrix display panel were made in 1954 (Skellet), the ignition of a discharge taking place at any intersection of two sets of electrodes. This technique was, however, limited to one cell at a time (2).

Since then, research has continued, the limiting constraining and contributing factors identified, and a host of different approaches have evolved.

All these are designated by the names of "Gas Discharge Displays" or "Plasma Display Panels" (P D P), the latter expressing the physical fact that when emitting light, matter is in its fourth state, made up of free ions and electrons.

Remark :

It will be noted that the vocabulary used here is not uniform. This results from the fact that ac and dc panels are not described by the same workers nor produced by the same manufacturers. Difference in vocabulary in most instances corresponds to different concepts or data. In order not to confuse specialists of either technology, the most usual wording in each case has been kept.

2 GENERAL PRINCIPLES OF OPERATION

A gas discharge has several properties which are particularly appropriate for display applications (3). A neon discharge, for example, emits sufficient light for an attractive display with an efficiency of about 0.5 lm W^{-1} . Appropriately chosen gases emit ultra-violet radiation that can be used to excite phosphors as they do in fluorescent lights. The gas discharge is characterized by an ignition (or striking or breakdown) voltage V_g (Fig. 1) above which an avalanche phenomenon takes place between the exciting electrodes and establishes the discharge with simultaneous strong emission of photons. As mentioned in another lecture of this series this threshold potential is of primary importance when the display consists of a matrix of cells. This self-sustained discharge is due to a space charge and high potential gradient at the proximity of the cathode. The I/V characteristic shows a negative impedance region, and the current is limited only by the series resistance. The discharge can be maintained with an applied voltage lower than V_g , down to a cut-off potential V_g where it extinguishes. On Fig. 2.a one can see the positive column, close to the anode and separated from the negative glow by the FARADAY zone. Fig. 2.b shows the potential distribution and Fig. 2.c the luminous intensity distribution (4).

Between the ignition V_B and extinction V_S voltages the cell can be either "on" or "off", depending upon the previous conditions and the arrangement : it can be used therefore as a bistable element (5).

In spite of this threshold, in multi cell arrangements unwanted cells with electrodes in common with "on" cells may also ignite. One reason for this ambiguous firing is that the glow discharges are low impedance elements which couple electrodes together. In order to avoid this coupling and to limit the flow of current, an impedance must be placed in series with each cell.

In 1963 Thompson (6) made a 10 x 10 array arrangement with one resistance associated to each cell, any of which could be selectively and concurrently turned "on" or "off". This was the precursor to dc gas discharge displays. In 1964 Bitzer and Slottow (7) realized that such an impedance could also consist of a capacitor. This prevented the use of dc since the discharge could not be maintained in the cell ; capacitive coupling is, however, compatible with ac. The ac plasma display panel was presented in 1966 (8).

At present, gas discharge displays are indeed classed as ac displays or dc displays (9). Both can be operated in storage or non-storage modes, storage meaning that the memory is inherent to the display device, whereas in the non-storage or refreshed or cycling mode, an external memory is added to the display and the information is sequentially transferred and refreshed frequently enough to avoid flicker, like in any other "non memory" display.

3 AC PLASMA DISPLAYS

3.1 General description

Most manufacturers produce ac P D P's of various sizes operating on the principle described in 3.2.

Fig. 3 shows a cutaway view and a magnified cross-section of a large ac plasma panel intended to display a great number of characters or elaborate graphics. It consists of two identical glass plates (1) imprisoning a gas (2) in which the discharge takes place. The inside surface of each glass plate carries rows of parallel conducting electrodes (3) insulated from the gas by a dielectric layer (4), made of materials which must also satisfy specific requirements, such as resistance to sputtering by ionic bombardment, lowered firing voltage, etc... In general it is not possible to have these electrodes made of transparent conductive material (like Indium Tin Oxide) due to the large surge current taking place when the discharge starts. The plates are assembled with their electrode networks orthogonal to each other and with a small uniform gap between them. In some realizations a matrix of holes in a thin plate was used to localize the cells but in most products this has been avoided and the cells correspond to the intersections of the two sets of crossed rows of electrodes. The gap is first evacuated and then generally filled with a neon-argon mixture which emits a characteristic red-orange luminescence with each electrical discharge.

3.2 Operating principle

In operation, a square-shaped ac voltage called the sustaining voltage is permanently applied to all X and Y electrodes : Fig. 4.a. (10). Its value is such that the electric field is not sufficient to initiate the discharge of the gas. In the absence of any other signal, the panel is in the "off" condition. Ignition of a cell, defined by the intersection of a line and a column is achieved by applying between them a writing signal, in the form of an auxiliary instantaneous voltage of proper phase exceeding the firing voltage, which initiates the discharge : Fig. 4.b.

The ions and electrons generated by this discharge will build up on the dielectric covering the electrodes creating an opposite potential ($-V_M$), and the actual potential

across the gas will drop causing the discharge to be rapidly quenched. During the next half-cycle, when the sustaining voltage presents a reversed polarity, the potential of the walls has no longer an adverse effect, but on the contrary, will add to the sustaining voltage, so that the resulting voltage is then sufficient to exceed the firing potential. A new discharge will occur with corresponding electron and ion deposit and then extinguish again; the addressed points (and only those) will continue to fire twice per cycle (once per half-cycle) of the sustaining voltage. The brightness will therefore be proportional to the frequency of the sustaining voltage, up to an upper limit, where there is no longer enough time for the charges to build-up on the walls and the memory effect no longer exists.

Extinction of a cell is achieved similarly by applying a short pulse of the proper phase to the appropriate pair of X and Y electrodes. A short discharge Fig 4.b takes place which cancels the stored charges and hence the corresponding memory potential ($-V_M$). The next half-cycle of the sustaining voltage will find the cell as if it had not been previously "on", and cannot therefore ignite it.

In other words, the panel has an inherent memory and any point can be selectively written or erased.

3.3 Physical characteristics

The shape of the display using a PDP is mainly determined by the dimensions of the panel itself. The thickness of the panel does not exceed 2 cm and its overall and useful areas are essentially related to the pitch of the cells and to their number. However operating constraints (high surge current, wave shape changes along long connections which affect the operation, etc.) impose that most of the drive electronics be placed immediately adjacent to the panel. The total thickness of panels with their drive electronics can be no more than 5 or 7 cm.

The front dimensions of panels (in these where there is no requirement for rear optical access) can be arranged so not to exceed the useful area by more than a few cm. Panels with 128 x 128, 128 x 256, 512 x 512, and up to 1212 x 1596 cells are available from different manufacturers with cell pitches ranging from 0.57 mm to 0.4 mm and with associated electronics allowing alphanumeric, semi-graphic, or full graphic addressing. The dimensions of these panels range from 10 x 10 cm up to 60 x 80 cm; the number of pixels from 16,000 almost $2 \cdot 10^6$ and in the alphanumeric mode a display capability ranging from some several hundreds to 40,000 characters.

The operating life of ac panels is very long, working hours in excess of 50,000 and failure rates of less than 0.04 % having been demonstrated. This is more than enough for military aircraft applications but, unfortunately, sacrificing on operating life would not provide a sufficient increase in luminance for much better legibility under the high ambient illumination that prevails in cockpits at high altitude.

The panels themselves are very sturdy and the associated electronics may be ruggedized without special difficulties. High altitude operation is made easier than for CRT's for instance, by virtue of the much lower voltages involved.

However, should the panel be exposed to low pressures, it would "inflate" due to the internal pressure of gas and some characteristics may change, resulting in erratic firing, or misfiring of cells. This effect however remains limited provided a proper design has been made.

The written information is stored without any need of "refreshing". The data input rate may be very low.

- Electromagnetic interference - Security. It must be noted that as in other devices where switching of rather large currents takes place, Electromagnetic Interference is produced. From the secrecy point of view, due to their acyclic type of operation, it is almost impossible to decode the data, and these panels compare very favourably with all other display media where the information is periodically refreshed or delivered through a fixed scheme (eg: TV raster; "Self-Scan" dc panels mentioned hereafter) which may

thus be easily deciphered. If stringent standards are to be met, special design of the panel and its drive electronics may become necessary. This problem has already been solved satisfactorily in France ; the remaining EMI, which is below most standards, is produced by the TTL circuits, rather than by the panel or its electronics.

3.4 Addressing, driving

The description of operation given above just mentions the main principles. In fact, the firing voltage and the "memory margin" vary somewhat from cell to cell due to manufacturing tolerances. On the other hand, although the frequency of the sustaining voltage is only about 50 kHz, the wave shape, the impedance of the source and the multiplexing technique used have a direct impact on the performance of the panel. The address circuits of most alphanumeric or graphic panels employ for multiplexing a network of two diodes and a resistor associated with each electrode plus high voltage driving amplifiers. This is still mostly done with discrete components in association with integrated diodes and resistors, resulting in high cost. As in electroluminescence, with which there are common requirements, the difficulty of integrating stems first from the high voltage involved : 100 to 170 V or even more, are required for some driving schemes, values which at present are uncommon in integrated circuits. To a lesser extent it results also from fast switching requirements, driving capacitive loads with large surge currents and "totem pole" output etc...

Thirty two channel 40 leads IC drivers for plasma panels are available, but prices and reliability still remain unfavourable due to a complex manufacturing process which implies several different IC technologies. However, EPIFET and DMOS approaches appear to be very promising solutions, and work is underway in several countries (USA, France, Japan).

3.5 System interface

Due to the close inter-relationship between panel and drive electronics, and the highly significant part of the price that the latter represents, most manufacturers provide the user with a "display function" incorporating the panel and factory-set drive electronics, which can be made very compact and sturdy. The system electrical interface is then reduced to a power supply and some TTL signals. In a typical alphanumeric panel, for instance, these will consist of :

- . "line" and "column" address of the character.
- . ASCII code of the character
- . Control signals : "Writing", "Selective erasure" or "Total erasure".

Graphic panels, of course, require more inputs.

Manufacturers offer a choice of panels with different sizes and organization : alphanumeric only, where characters may be written in a predetermined format (5 x 7 ; 7 x 9 ; 8 x 10 ; 10 x 10 pixels) ; graphic, where any element may be driven independently ; or semi-graphic, where elements may be addressed independently but in a predetermined "block" of pixels.

3.6 Visual characteristics

-The most important visual feature of an PDP's is the quality of the display: It is absolutely flicker-free thanks to the high supply frequency (2,000 times the eye's image fusion time, with two ignitions per cycle). No image break-up or stroboscopic effect (temporal aliasing) occurs in the case of relative motion between the observer and the display as opposed to "refreshed" displays (CRT's, scanned dc plasma panels or certain electroluminescent panels). Each point is perfectly located so that no distortion occurs and the pattern remains steady and free from any jitter. Therefore, there is no noticeable fatigue of the eye even after a long observation time.

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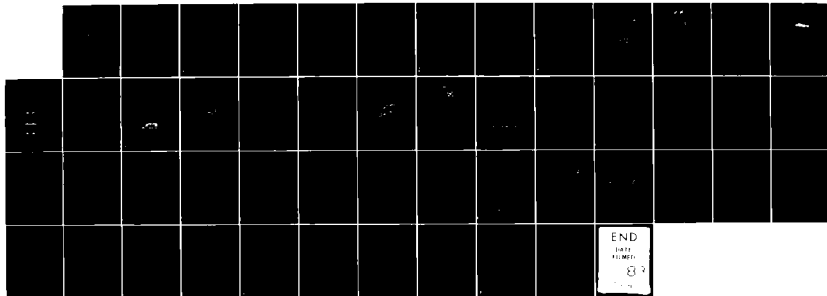
MODERN DISPLAY TECHNOLOGIES FOR AIRBORNE APPLICATIONS
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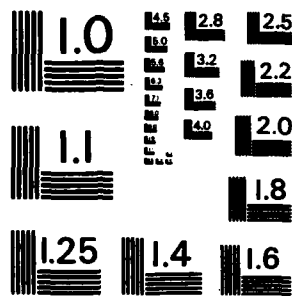
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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS - 1963-A

-The color orange is typical of the neon-argon gas mixture.

-The available resolutions (0.4 mm pitch) are already good enough to permit the display of alphanumeric or graphic data observed from a typical distance of 40 cm without noticeable effect (spatial aliasing) resulting from the discretization ; this in accordance with the eye's characteristics. Large panels with increased resolutions

(25 % : 0.3 mm pitch) have been designed and are in production. -The viewing angle is very wide, close to 180° with a dip in luminance on the perpendicular to the panel. This is due, as for many matrix displays, to the presence of the column conductors on the front glass sheet which, even if transparent, partly hide the discharge.

-Moreover, by proper arrangement of the drive electronics, it is possible to give access to the rear face for the addition of data, either by projection on a matt finish, or through direct superposition, by taking advantage of the transparent nature of both constituting plates.

-As the glass sheets are transparent and as no diffusing material is in contact with them (like phosphor in CRT's or electroluminescence), the contrast is good even on bare panels. It may be further improved by the addition of an absorbing material at the rear, and an anti-reflection coating.

There are, however, two shortcomings which restrict the use of these panels in a military aircraft environment :

-The luminance is limited to 200 or 300 cd m⁻². This does not allow usage in demanding applications like H U D, although this may be sufficient for fuel management, area navigation, and of course, all crew compartment use.

-Dimmability is limited to a ratio of 3 or 4 to 1. This dimming can be obtained by two ways, either by changing the sustaining voltage frequency, thus varying the luminance of the whole display, or erasing and re-writing selectively only a part of the display which gives "shades of grey".

Color

No color ac PDP's are available industrially although the feasibility of multichrome panels has been demonstrated (11)-(12)-(13). In the multichrome approach, sets of three properly located pixels (trios or stripes) are coated with different phosphors, and the sensation of hue results from the addition, within the eye, of the three stimuli so obtained in the very same way as in a shadow-mask CRT. The price paid for color capability is a drop in resolution, since three luminescent sites are used to present one perceived element.

In a similar way, monochrome displays with different colors from the neon-orange (eg. green) can be made where a single phosphor is used. In both instances the gas mixture is generally replaced by Xenon, which yields a higher U.V. content, which in turn improves phosphor excitation. However, unless cells are defined by holes in a non U V transmitting material, and indexed with electrode crossings, optical crosstalk can take place, these two reasons cumulating to make it difficult to achieve good resolution in color.

3.7 State of development

Invented 15 years ago, ac panels have only recently been extensively employed.

First uses were found in non-military applications, like the PLATO automated teaching system, for which they were indeed first designed, and banking and air traffic control terminals. They are finding widening acceptance in the military field, mainly in Command and Control functions, such as in US Submarines ; US Navy's DIFAR ; US Army's DIVAD and SST ; MIFASS program (Marine Integrated Fire and Air Support System) ; the French ATIBA (artillery control) system and the UK PTARMIGAN program, and in several Electronic Counter Measures (ECM) systems.

They are generally used in the alphanumeric mode, although in some applications provision for semi-graphic or even full graphic addressing is made allowing cyrillic, arabic or kana characters to be displayed, together with symbols and drawings. All of these may be superimposed on a map placed at the rear face.

No pictorial TV-like applications are known to be under consideration.

Once again, the limitations do not come from the panels themselves, but rather from the associated electronics. Attempts have been made actually to produce animated TV-like pictures with several shades of grey, one of the most promising approaches being based on the "dithered order" principle (14) - (15).

To summarize, one can say that at present, ac panels with dimensions of up to 45 cm (60 cm diagonal) are available and up to 1 m wide have been demonstrated (16), panels with resolutions of 0.3 mm (83 l/inch) will be available in the very near future and up to 0.25 mm have been demonstrated, alphanumeric and graphic displays without half-tones are common-place, military environment extremes are, or can be fulfilled, and color and full image characteristics have been demonstrated and can be produced at the expense of a complex electronics which remains the weak point of ac PDP's until high voltage integrated circuits (in technologies convenient for both plasmas and Thin Film Electroluminescence) are themselves available. Luminance remains a limitation.

4 DC PLASMA DISPLAYS

4.1 General description

Most of what has been said for ac plasma displays applies to dc plasma displays. The major differences with the description of the former, given in 3.1, are that the electrodes or resistive extensions thereof are directly immersed in the gas mixture, and that in most cases, it is necessary to add a stencil plate. The holes of stencil plate are registered with the crossing of the electrodes and thereby localize the cells. This is generally necessary to limit the consequences of electrodes sputtering by ion bombardment, or for separating the display discharge from the transfer discharge (see below). This obviously adds to the difficulties in manufacturing the panel.

4.2 Operating principle

Various principles can be used to operate dc gas discharge panels, but basically they are supplied with a unidirectional voltage, either pulsed or sustained, the latter giving the memory mode (17)-(18)-(19)-(20).

Individual cells are struck on by application of a voltage pulse in the range 150-200 V. As soon as a stable discharge has been established, the cell impedance drops significantly, and it is therefore necessary to provide a series resistor to limit the current flow in the cell. Most commercial matrix panels are multiplexed in the pulsed mode and because only one line of the display is addressed at any one time, it is only necessary to provide a resistor in series with each column driver. This drive technique, however, yields a rather low brightness (150 cd m^{-2}). Where high display brightness is required, as in the aircraft cockpit, it is necessary to operate the display in the memory mode, in which an addressed cell is active for almost the whole of the frame time, thereby yielding a much higher mean brightness. The memory effect is achieved by striking a cell on, as described previously, and then reducing the voltage to a level high enough to sustain the discharge but too low to ignite adjacent cells. The main disadvantage with this drive scheme is the necessity of a limiting resistor in series with each individual cell in the display.

The difference between the strike voltage and the maintaining or sustaining voltage is known as the working margin. The spread which occurs in these two panel voltages due to the manufacturing tolerances presents a further difficulty for memory operation.

Degradation of the working margin results in non-uniform operation across the display.

A third problem is the statistical time lag between application of the trigger pulse and the establishment of a stable discharge in the cell - an effect known as jitter. This poses no difficulties for the ac plasmas thanks to the high frequency of the sustaining voltage but does pose problems with operation in the memory and the pulse modes of dc plasmas. In order to minimise jitter, it is necessary to prime the cells by introducing ions or electrons into the cell, prior to the application of the strike voltage. This is normally achieved by incorporating priming cells into the panel in close proximity to the data cells. The priming cells are blanked from view, so that their light emission cannot be observed.

The priming effect, which is the ability to use one discharge to affect a neighbouring site, and thus manipulate the position of the discharge, is unique to gas discharge displays. Fig 5.a illustrates how the striking voltage V_B varies with the distance from an active site: the closer they are, the lower V_B is. Therefore, by just using a three phase voltage variation applied on scan electrodes it is possible to shift the discharge from cell to cell: Fig. 5.b. This principle is used in the device known as the "Self-Scan"® Fig 6-(21). At some cost in the panel complexity, this device exploits glow priming and transfer techniques to provide considerable reduction in circuit complexity and cost. An exhaustive description of this device may be found elsewhere in ref. 9.

The priming effect is also used in a device more recently described, able to display several lines of 80 characters and intended for small basic word processors (22). The self-scan mode, however, suffers several limitations regarding display size, brightness and number of displayed elements, which restricts its application mainly to cash registers and banking terminals. In order to simplify the electronics, these panels are activated by a multiplexed scanning signal along the rows and columns of the matrix. The frame scan must exceed about 50 Hz and a row cannot contain more than 300 dots, otherwise flicker becomes quite noticeable and the display dims. Therefore, these panels are limited to purely alphanumeric display of about forty 5 x 7 pixels characters per row. To overcome some of these limitations, a modified type of operation has been described (23), combining ac 16.7 kHz operation for memory display and "Self-Scan" dc drive. Fig 7 is a cutaway view of the design, and Fig 8 shows the wave forms for the different voltages, as can be seen they look quite similar to those shown on Fig.4.

A thin metal plate with holes in it, called the priming plate, separates the discharge space into a front memory section operated in the ac mode, and a rear, dc operated, scan section.

The front plate is coated with a transparent continuous conductive layer, itself coated with an insulating layer. The stencil priming plate is also covered with an insulating layer. The result is that all cells in the memory layer are connected in parallel. Each cell is isolated from its neighbors by the glow isolator mesh. These two insulator covered plates, when fed with an ac voltage provide the memory capability. Scan anodes are located at the bottom of grooves in the rear plate. Six phase cathode wires can be seen in the figure 7, orthogonal to the anodes and isolated from the priming plate by glass stripe spacers. Operation of the scan section is similar to that of earlier refresh type "Self-Scan" displays, except that scan is initiated only when changes are required in the display content.

This configuration claims to allow the display of over 96 characters per row without flicker, with improved luminance and multiplexing possibility which reduces the number of address lines to about one tenth of those required to address each pixel. It has still to be demonstrated that this economy is large enough to balance the added cost in manufacturing the panel, and whether this design might be compatible with displays, other than alphanumeric.

4.3 Physical characteristics

The front dimensions of dc PDP's together with the associated electronics, do not significantly differ from the useful area, as is indeed the case for ac panels, and their

thickness is also in the order of several centimeters.

- The commercially available panels have a display capability from 1 row of 16 characters up to 12 rows of 80, while an alphanumeric and limited graphic unit contains 17 lines and 192 columns. A panel of 128 x 128 elements has been reported. The number of characters then ranges from 96 to 960 and the overall length is around 30 cm.
- The poor resolution results from the coarse pitch (0.75 mm horizontal ; 1 mm vertical). This may be considered adequate for alphanumeric character display but is unlikely to give sufficient resolution for vector graphic display. Further development of the technology to provide finer pitches is likely to be limited by the mechanical tolerances of the panel components, cross-talk caused by the close proximity of adjacent cells, and by tolerances in the resistor arrays.
- The operating life expectancy is 30,000 hours under normal conditions. However this can be drastically impaired (to, say 100 hours) for panels operating below 10°C, and which contain mercury, as it is usually the case for dc panels ; and for these at least, no operation at all is possible below 0°C. The Hg vapor in the gas mixture is necessary to avoid sputtering of electrode material. At low temperatures, the Hg protective effect is greatly reduced, therefore bringing about an increased rapidity in electrode deterioration.

4.4 Addressing - Driving

As has been seen in paragraph 4.2 there are several different ways for operating dc panels, and the requirements are still more closely related to the panel design, than for ac ones. Therefore the vast majority of dc panels are supplied with the drive electronics (except perhaps for some single character-row types) and the interface is reduced to supply and logic.

4.5 Visual characteristics

- As in all other matrix displays, the picture is distortion free and each element is precisely located.
- In most designs, holes in a stencil sheet define the cells. If the cathode, and hence the discharge, is not located on the front surface (or on top of the hole) the viewing angle may be lower than for ac panels, not exceeding a cone of 100° to 120°.
- The color is neon-orange or green, the latter being obtained by the use of suitable U.V. activated phosphors. The phosphors are coated onto the cell walls and are activated by the U.V. emission in the gas discharge, in which case Xe is incorporated in the gas to enhance U.V. emission. Several manufacturers market displays incorporating phosphors which emit in the green. This however, further restricts the viewing angle, and produces a color shift from green to reddish yellow and red when changing from the orthogonal to the lateral viewing position. A matched green filter should obviate this effect, and since the contribution from the glow to the total luminance is small, the reduction in luminance should be small too.
- The major pitfall of these panels when operated in the pulse mode is the flicker, (which imposes a refresh frequency of typically 70 Hz, thus limiting the number of cells per line as mentioned) and a display "break-up". This is particularly true for panels with no phosphor coating, but in spite of the decay time added by phosphors, it remains objectionable to dc panels where such a coating is used.
- The luminous efficiency (0.5 lmW^{-1}) yields a mean pulse mode driven panel luminance in the range of 100-150 cd m^{-2} which, as stated previously, is inadequate for good legibility in conditions of high ambient illumination. Some panels, which are pulse driven, have a quoted mean brightness of 60 to 100 cd m^{-2} . For very high brightness displays, memory addressing techniques are used, as described for example by Smith experimental display. The panel can be operated at a luminance as high as that found in CRT's, but

the current density required to do this involves excessive sputtering of the cathode material, and the life of the panel is significantly reduced.

Panels displaying 7 rows of 15 characters each having a 7 x 5 format, which can be operated in the memory mode at up to $1,000 \text{ cd m}^{-2}$ have been produced. The basic inefficiency of the discharge mechanism, combined with energy dissipation in the series resistors, means however that considerable heat is dissipated at these high luminance levels. In the long term, the dc gas discharge panel does not appear to be as promising for aircraft use as the thin-film EL panel.

- Dimming

A dimming ratio of 5 : 1 for the "Self-Scan" displays has been quoted, but because of the visibility of the scan-glow, legibility in dark environments is impossible. It is desirable that panels for aircraft cockpit be sufficiently bright to be legible under 100,000 lux and should have a dimming ratio of 1,000 : 1. Drive circuits for high brightness panels have been developed in the U.K. which enable dimming ranges greater than 500:1 to be achieved.

4.6 State of development

Existing dc plasma panels have been specifically developed for the display of a few hundred alphanumeric characters, and have found applications mainly in bank teller's terminals, industrial process management, etc... There are at present no commercial panels suitable for the display of vector graphic information. A dc panel offering a very high resolution (0,2 mm pitch) and operating with low driving (180 V) and switching (30-50 V) voltages has been described recently (24). Moreover the number of drivers can be significantly reduced. It is based on the addition of a set of trigger electrodes on the back of the panel, isolated -and therefore capacitively coupled-to the cathodes (Fig.9). When an appropriate voltage is applied between the trigger electrode and a cathode, (Fig.10) charges build-up on the wall in a short time up to a voltage where the trigger discharge stops in a way very similar to that of ac panels. But if an anode voltage is raised from its biased level to a value V_p high enough, the trigger discharge is transferred between cathode and that anode and a glow discharge takes place within a few microseconds. V_p can be set at a value lower than the striking voltage and higher than the extinction voltage without trigger assistance. A panel with a single trigger electrode can therefore operate on low supply and switching voltages. In case of multiple trigger electrodes associated with several cathodes, multiplexed operation is possible with the additional advantage of fewer cathode drivers. As the panel structure is fairly simple high resolutions are also possible. In an experimental 512 x 256 pixels panel a resolution of 0,3 mm has been achieved, a luminance in excess of 80 cd m^{-2} and a contrast of 50:1 have been obtained at 60 frames per second. 512 anode (column) drivers, 32 cathode (lines) and 16 trigger drivers were used.

Little work has been published on the performance of matrix addressed conventional dc plasma panels over the full military environmental range. It is not anticipated that there will be any problems caused by vibration specification of panels operating in military aircraft cockpits. However it would be necessary to control temperature and pressure as mentioned.

The brightness of displays presently available from the two major manufacturers of dc panels is inadequate for full sunlight viewing, but it is hoped that panels under development will have sufficient brightness while maintaining the characteristics of life expectancy and temperature independence.

The US Army has been employing the "Self-Scan" in Digital Message Device development models, and a panel of 7 rows of 15 characters is used in the flight management system of the Lockheed 1011-500 commercial aircraft. Provided suitable contrast enhancement techniques are applied, reasonable legibility may be obtained under 100,000 lux ambient illumination, as met in a military aircraft cockpit at high altitude.

Studies have been carried out in order to develop color TV plasma panels, by using dc structures in conjunction with photoluminescent materials. In general these devices use positive column discharge which allows a better luminous efficiency necessary for TV pictures presentation without excessive power consumption. Nevertheless, none of these studies have reached the commercial stage.

To summarize, dc PDP's have up to now been produced for non military, alphanumeric applications with limited size, number of characters, and low resolution. Although they have the inherent capability of displaying half-tones, this seems to have been little employed. Their high brightness capability in the memory mode may be hindered by life expectancy problems, particularly at low temperature, and heat dissipation.

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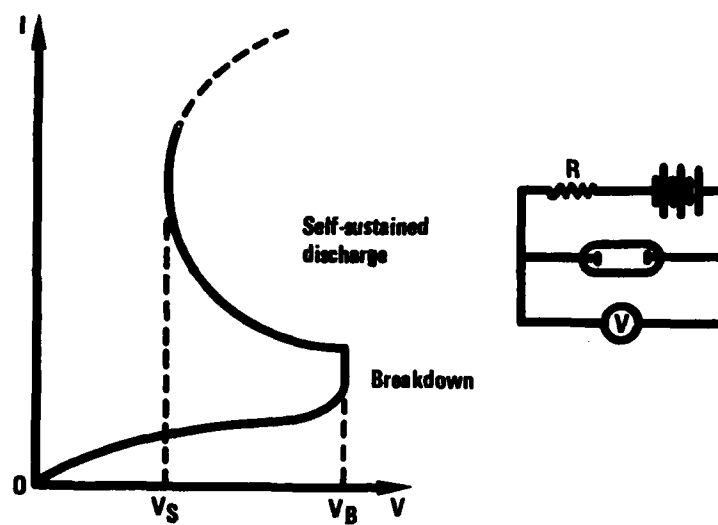


Fig.1 Characteristics of gaseous discharge

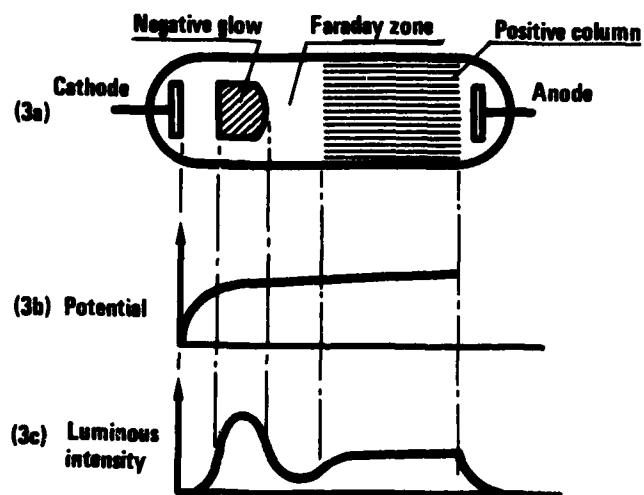


Fig.2 Gas discharge: potential and luminous intensity

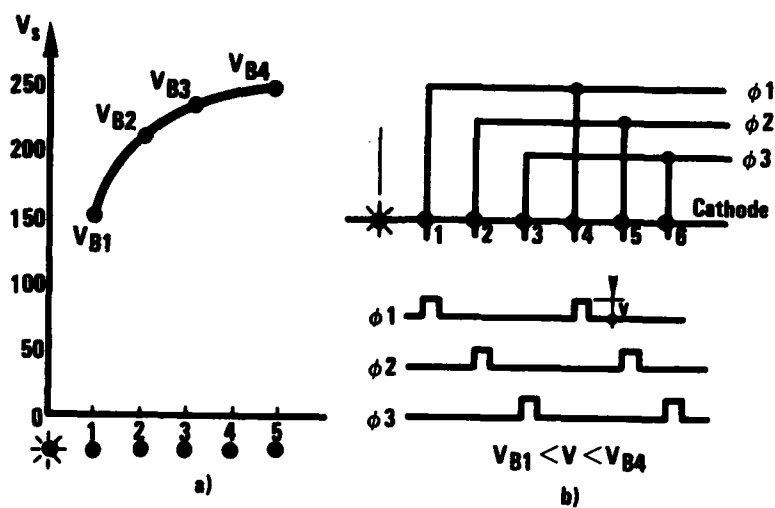


Fig.5 Priming and shifting mechanism

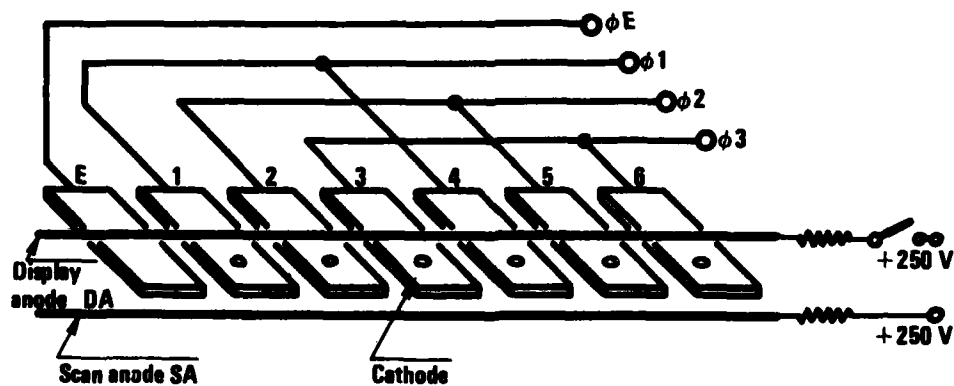


Fig.6 Self-Scan® schematic structure

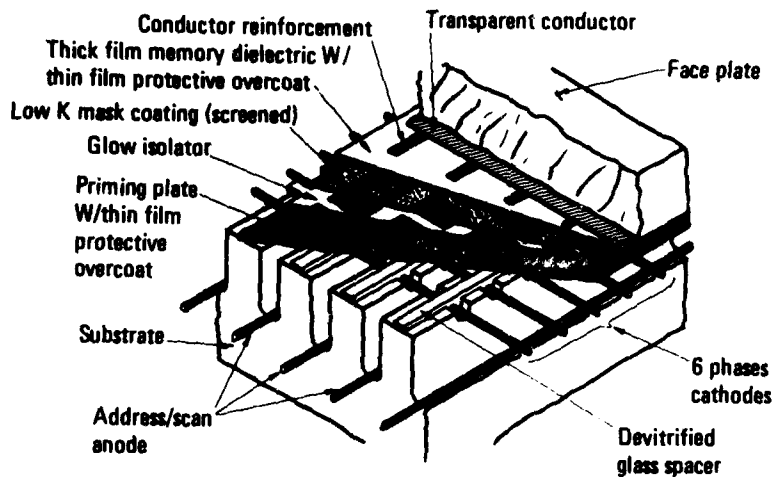


Fig.7 Self-Scan with memory display panel structure

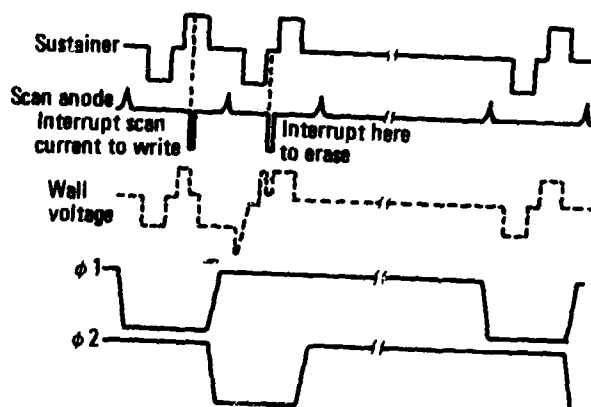


Fig.8 Self-Scan with memory addressing wave forms

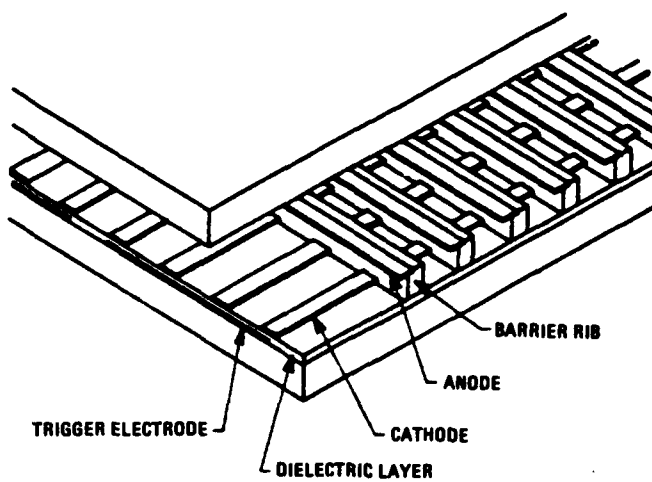


Fig.9 PDP with trigger electrode structure

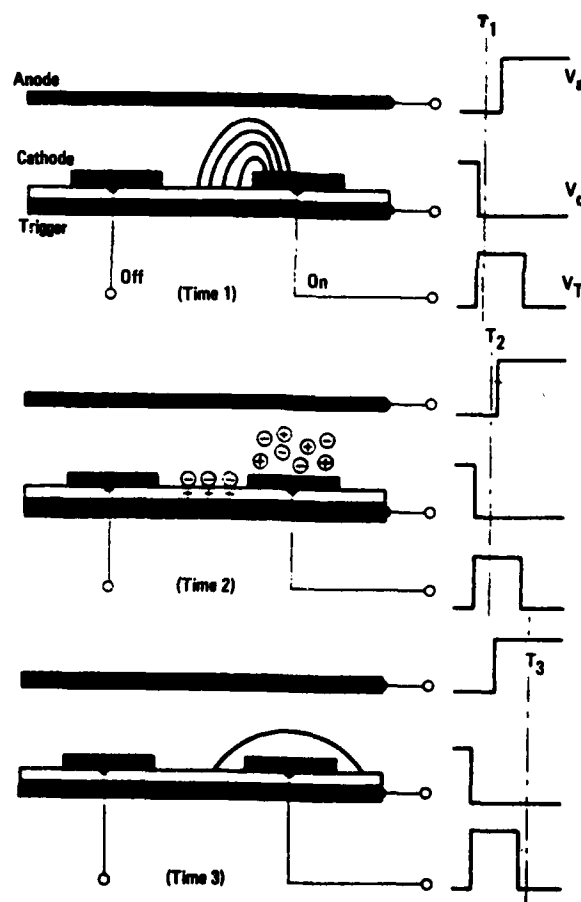


Fig.10 PDP with trigger electrode: principle of operation

OTHER TYPES OF DISPLAY

by

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SUMMARY

The other papers in this series have dealt with the majority of display technologies that have passed through research and development and reached commercial production. This paper covers a selection of newer and less well advanced display technologies that still need further development before commercial or military acceptance can be assured. The approaches to be covered are all non-emissive and include magneto-optic, magnetic particle, electro-chemical and various electro-mechanical displays. The electro-chemical displays can be conveniently sub-divided into electro-phoretic, electro-chromic and electro-plating types. The properties and limitations of these various techniques are reviewed and compared with those of the more established liquid crystal displays.

I INTRODUCTION

This paper attempts to review a variety of display technologies that have not been discussed elsewhere in this series. No attempt is made to be exhaustive, and the only criterion for inclusion of a particular approach is that there have been recent publications on that approach, indicating a continuing active interest.

The range of effects includes the following, in the order in which they are discussed:-

- 1) Electro-chemical effects, which may conveniently be split into two groups, electro-plating and electro-chemi-chromic;
- 2) Electrophoresis, and the closely related "suspended particles" effect;
- 3) Electro-wetting;
- 4) Magnetic effects of two main types, "magneto-optic" and "magnetic particles";
- 5) Electro-mechanical effects of various types.

All these displays are like liquid crystals in that they do not emit light, they are "light modulators" merely controlling the transmission or reflection of light from an independent source. Consequently, in assessing the potential of these new effects, it is natural to compare them with liquid crystals, the most firmly established light-modulating display technology. To facilitate this comparison we should first review the strong and weak points of liquid crystal displays (LCDs). This is not an easy task since LCDs encompass such a wide range of techniques and optical effects that broad generalizations are almost impossible. Indeed, it can be argued that this wide range of effects is one of the most advantageous features of liquid crystals.

Dealing with low complexity displays first, the low voltages and low currents required are ideal for battery operation with low cost drive electronics. A wide range of sizes and resolutions is possible for use either in transmission or reflection. Simple displays are very cheap in mass production and have excellent life. Memory effects, particularly in smectic LCs, are proving significant in high complexity displays.

Conversely, the visual appearance of "twisted nematic" (TN) displays is far from ideal, with limited angle of view, low brightness and often poor contrast. Incidentally, the definition of contrast ratio used here is simply "brightness of ON-state: brightness of OFF-state". Their operating temperature range is limited to roughly -20 to +80°C, and response speed is poor below 0°C. Displays with adequate complexity for TV-type applications are possible, but require special expensive structures and are only available in small sizes.

With these strong and weak points of LCDs in mind we can now examine the alternative approaches.

The construction used in many of these alternative display technologies as shown schematically in Fig. 1 is basically similar to that of an LCD. In outline it consists of a back-plate separated by a small distance from a front plate with some active fluid in between and an edge seal to control spacing and to contain the fluid. The front plate is made of glass with a patterned transparent conductor on its inner surface. The back plate may be opaque or transparent and carries appropriate electrode patterns on its inner surface.

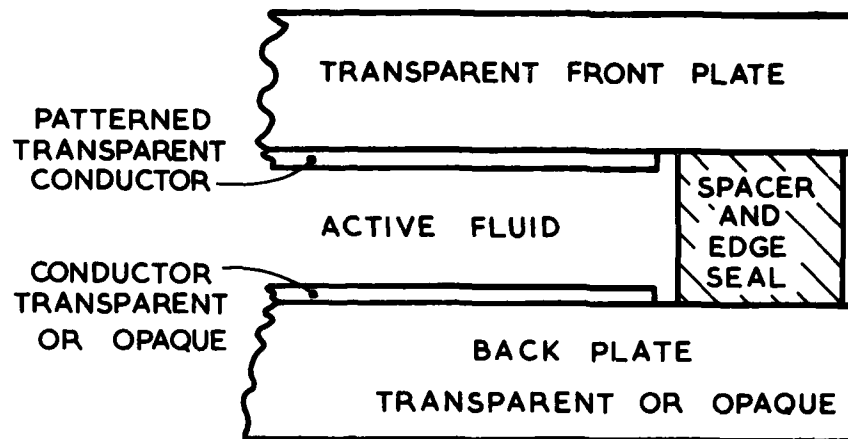


Figure 1. Schematic of Typical Display Structure.

II ELECTROCHEMICAL EFFECTS

The majority of "electro-chemical" effects used in displays are obtained in devices derived from the general construction of Fig. 1. Two distinct classes may be defined:-

- 1) "Electro-plating" effects, where low voltage electrolysis deposits or removes an opaque solid layer at one of the electrodes;
- 2) "Electro-chemi-chromic" effects, where the absorption spectrum of a layer of solid material, permanently adhering to one electrode, is altered by the action of the ions passing through the electrolyte.

It should be noted that these definitions are not universally recognized, whereas the term "electro-chromic" may be used indiscriminately for all devices acting via electro-chemical processes.

Two types of electro-plating systems have been extensively researched: an inorganic approach in which a thin layer of deposited silver is the absorber, and an organic approach using various members of the viologen family.

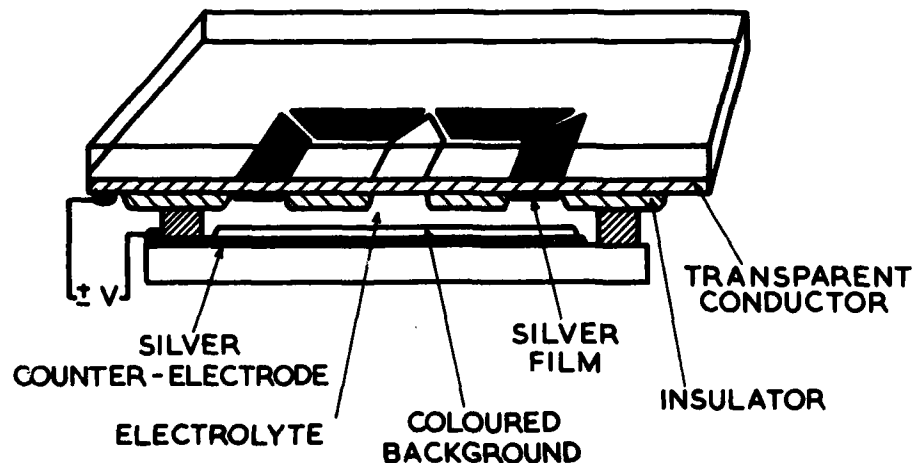


Figure 2. Silver Iodide Electro-plating Display.

One version of the "silver" type, shown in Fig. 2, uses silver iodide dissolved in organic solvents as the electrolyte. The basic plating reactions of the silver are not precisely reversible, so plated silver tends to remain on the electrode after the erase cycle. However, a beneficial side-reaction involving the iodine occurs which tends to re-dissolve the residual silver. One feature of this effect is shared by all electro-chemical displays. The written state acts as an ordinary battery cell, generating potentials that tend to discharge the cell and automatically erase the written information. If elements can be electrically isolated no current can flow so long term memory is possible. Otherwise, although there may be significant short term memory, the data must be refreshed regularly, typically every few minutes.

A prototype silver plating display has been described by Mayer et al (1, 2), requiring $\sim 1 \text{ mA/mm}^2$ at 1V and achieving reflective contrast ratios $\sim 4:1$ with response times $\sim 200 \text{ ms}$. The display had a black on-state viewed against a bright, diffusing background with full 180° angle of view. The operating temperature range was from -40 to $+80^\circ \text{C}$. Lifetime was limited by poor reversibility at low temperatures and by the high internal pressures generated by the organic solvents at high temperatures. No threshold voltage existed to permit multiplexed addressing.

Viologen-type displays differ from the above in that the plated-out coloured material is an electrical insulator. Although this inhibits the generation of very thick layers, it does ensure that the film is of uniform thickness. The lifetime of these displays has been limited by the lack of complete reversibility of the main reactions, coupled with undesirable side reactions. The problems of matrix addressing have been discussed by Arellano et al (3) who demonstrated an 8×144 element dot matrix. Unfortunately, few details of the chemistry or performance of this prototype were published. The poor threshold characteristic for matrix addressing has been overcome in another way by Barclay et al (4), who used a large area Si integrated circuit as the back-plate of a reflective cell, driving the elements of a 64×64 array by a matrix of MOS transistors. In this way response times of a few milliseconds were obtained using current densities of less than 0.5 mA/mm^2 .

The distinguishing feature of the electro-chemi-chromic effect is that the flow of current through the electrolyte does not deposit or remove opaque material at the electrode, it merely modifies the properties of a layer of material already present on the electrode. The best known and most extensively used materials whose optical properties can be altered in this way are tungstic oxide, WO_3 , (5-8), lutetium diphthalocyanine (9, 10) and iridium oxide (11, 12).

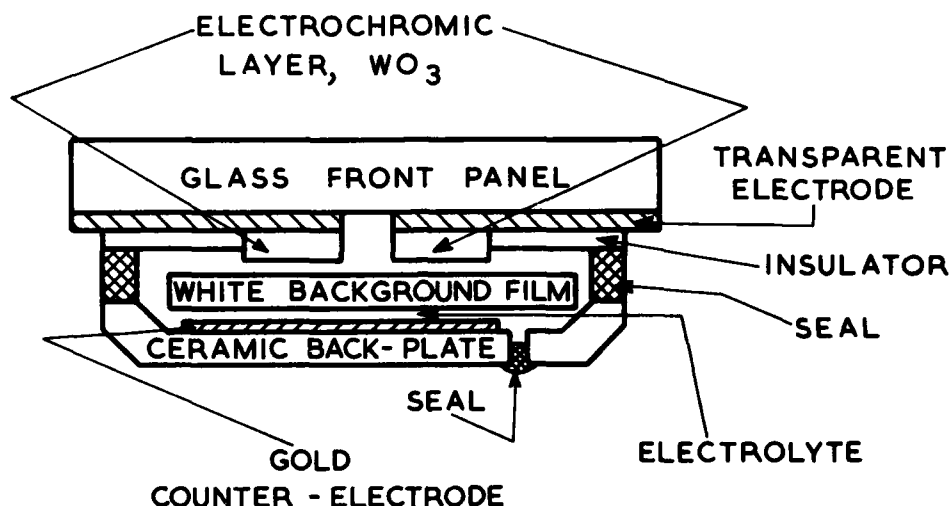
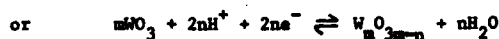


Figure 3. Construction of WO_3 Watch Display, from (7).

A simplified structure for a WO_3 cell is shown in Fig. 3. WO_3 is deposited by evaporation as a thin layer onto a transparent electrode which then forms the front plate of a sandwich cell, filled with a suitable electrolyte. The as-deposited WO_3 is transparent, but has a strong infrared absorption band. When the WO_3 plate is used as the cathode it is reduced to a blue-coloured form having a broad absorption band peaking near 1000 nm but spreading over much of the long-wavelength part of the visible spectrum. The film then appears dark blue. There is some debate concerning the precise details of the electro-chemistry, two simple proposed reactions being:-



In these reactions the electrons come from the cathode and the protons (H^+) come from the electrolyte. A major problem with this type of device has been the long-term instability in the often highly acidic, aqueous electrolytes. Alternative systems, however, have replaced the H^+ ions with alkali ions (Li^+ , Na^+ , etc) in non-aqueous electrolytes. Unfortunately, the bulkier alkali ions diffuse more slowly through WO_3 than protons, so response speeds are poor. For example, Miyoshi et al (7) used electrolyte solutions of lithium chlorate in propylene carbonate. Although care was taken to deposit the WO_3 in a highly porous, amorphous form, the response time for 2:1 contrast ratio at room temperature was $\sim 1 \text{ s}$.

Other workers have used solid electrolytes with various mobile ions (H^+ , Li^+ , Na^+ , etc.). All of these approaches have achieved strong colouration but have responded very slowly owing to the poor ionic conductivity of solid electrolytes. The most promising solid electrolyte system (6) used a proton conducting polymer from the sulphonic acid group and achieved operating life of greater than 10^7 cycles with over 3 years shelf-life. The switching speed was rather slow at room temperature, requiring nearly 1s to write or erase with 3:1 reflective contrast ratio. At present WO_3 technology achieves performance that is just acceptable for simple clock displays, but must overcome several problems before higher complexity displays will be possible.

A similar, more recent system uses iridium oxide as the electro-chromic layer, which is produced either by reactive sputtering or by anodization. The electro-chemistry of these films appears similar to that of WO_3 in that H^+ , Li^+ and Na^+ can all cause colouration, but there are significant differences in detail. To the observer, the coloured films appear black. Other advantages include faster colouration and bleaching ($<250\text{ms}$ for 2:1 contrast at room temperature), better stability ($>10^7$ cycles, even in highly corrosive electrolytes), and response speeds almost independent of temperature.

The third group of electro-chemi-chromics is the rare-earth diphthalocyanines. In particular, the lutetium form is notable for its multi-colour capability which depends on the potential to which the film is charged. The film colour changes from violet at potentials below -1V , through blues greens to yellow and orange as the potential is raised, finally reaching red at $+1\text{V}$. All the coloured states of the material are insoluble in the aqueous KCl electrolyte, and the individual colours have long-term open-circuit memory. Switching times (9) between colours can be less than 50ms , even at -50°C with an appropriate electrolyte. To date no information is available on the matrix addressing capability of this approach, and one can only speculate on how the multicolour capability could be used.

III ELECTROPHORESIS

In an electrophoretic display changes in reflectivity or colour occur as a result of the movement of charged solid particles in a dye solution under the influence of an electric field, as shown in Fig. 4. This type of display has been investigated for many years, but only a few recent publications will be discussed here. More extensive coverage of earlier work is found in (13).

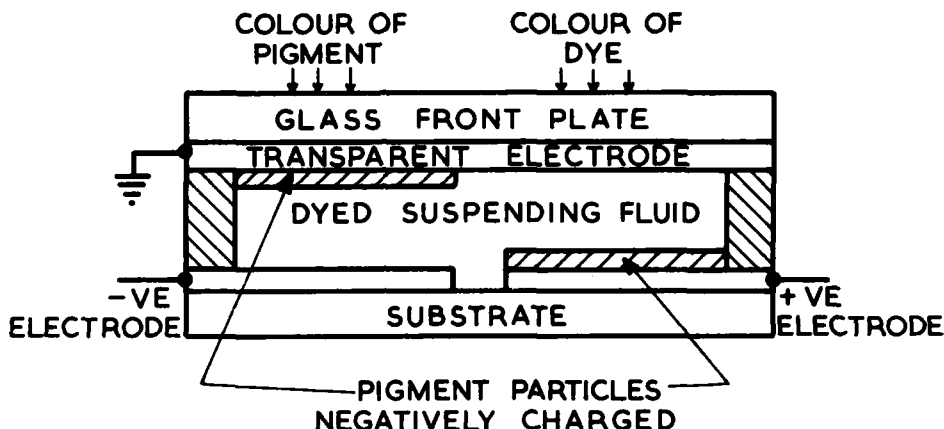


Figure 4. Electro-phoretic Display, showing ON and OFF Elements.

The majority of early displays used sub-micron TiO_2 particles in various opaque solutions and achieved excellent contrast and viewing angle. Several problems were encountered, however, including:-

- 1) the particles tended to flocculate;
- 2) the particles tended to sediment out, being much denser than the solution;
- 3) fringing fields between display elements caused transverse migration of particles;
- 4) there was no obvious threshold in the voltage response curve, so matrix addressing was not possible.

More recent work, particularly on the nature and magnitude of the attractive and repulsive forces between particles, has brought about many improvements. By control of the particle surfaces and the constituents of the suspending fluid Chiang (14) developed a system where a small potential barrier existed between particles which tended to prevent flocculation. When a threshold electric field was exceeded, however, this barrier could not prevent close packing of the particles, where short-range attractive forces gave a second stable state with long term memory. In this way flocculation was prevented, permanent memory of written information was obtained, and when special drive waveforms were used a threshold for matrix addressing was achieved. To demonstrate the effects a $1''$ square, 32×32 element display was made. The drive scheme required 50 to 80 V, but line times as short as 35ms were achieved. No data was given on the brightness or contrast ratio.

The problems of gravitational sedimentation and particle migration in fringing fields have been tackled by Hopper and Novotny (15) who used a patterned photo-polymer to subdivide the display cell into $50 \times 50 \mu\text{m}$ sub-cells. Although the stated problems were overcome, some loss of visual contrast resulted.

An alternative method of reducing gravitational sedimentation, by polymer-coating each TiO_2 particle to match its net density to the suspending liquid, also resulted in considerable loss of contrast.

Chiang and Fairburn (16) have used a plate of "Varistor" material as the back-plate of the display to improve the matrix addressing capability. The operating principles were similar to those used for LCDs, in that each display element was electrically in series with a discrete Varistor device. The highly non-linear, symmetrical I-V characteristics of the Varistors provided the threshold voltage needed for matrix addressing. For satisfactory operation the capacitance of the Varistors had to be minimised, and a subsidiary capacitor was needed for charge storage at each element, so the design and construction of the varistor plate was quite complex. Chiang reported a yield of >90% of operating elements in a prototype display containing 32 x 32 elements in a 1" square cell. The drive requirements of this prototype, 20 μ s pulses of ± 70 V, indicated that up to 1000 lines could be written in 20ms. The electrophoretic memory ensured that continual refresh of data was not needed. No mention was made of the visual or environmental properties of this prototype.

Very little recent quantitative data is available on the visual appearance of EP displays. Generally it is concluded that viewing angles are excellent, comparable to ink on paper. Values of brightness and contrast of TiO_2 based devices should in principle be excellent, but the steps required to achieve usable stability and life in these devices have a detrimental effect on both brightness and contrast. A recent paper by Fitzhenry-Ritz (17) using non-sedimenting pigment particles achieved maximum brightness values of about 30% of standard matt white, but only at unusably low contrast. With adequate contrast, say 4:1, the brightness had fallen to around 15%. It is not clear whether these figures are typical of other types of electro-phoretics.

IV SUSPENDED PARTICLE DISPLAY

The "suspended particles display", reported by Saxe et al (18), and sketched in Fig. 5, consists of a colloidal suspension of long, thin, absorbing particles in a transparent liquid. With no voltage applied to the cell the particles are randomly orientated and the suspension is strongly absorbing. When an adequate AC electric field is applied the particles all align parallel to the field and the cell becomes transparent. As with EP displays, recent developments have concentrated on density matching of particles to the suspending liquid to prevent sedimentation, and on drive methods and particle surface treatments to prevent coagulation. Results on test cells suggest excellent values for contrast and angle of view, but values of on-state brightness were not quoted. As with many other display techniques, values of contrast may be traded off against brightness. Turn-on and turn-off times were 100ms and 300ms respectively with less than 10V RMS drive at 20°C. No mention was made of performance at low temperatures or with multiplex drive. Survival tests at 85°C were encouraging.

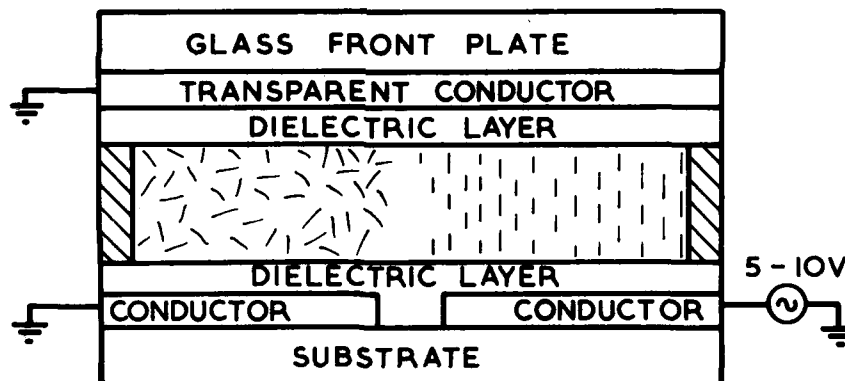


Figure 5. ON and OFF states of Suspended Particles Display.

V ELECTROWETTING

This effect relies upon the dependence on electric fields of surface tension forces at liquid-solid or liquid-liquid interfaces. It has only recently been considered for display applications and is at a very early stage of investigation. Basically, the presence of an electric field at an interface can significantly alter surface tension forces and cause rapid movement of fluids in very small capillaries. Two display configurations have been suggested (19). In the first the mobile fluid moves into and out of the pores in a transparent porous plate. When the plate is dry it scatters light strongly and appears matt white. When it is fully wetted by a liquid of identical refractive index, it is completely transparent.

In the second configuration a slug of mercury is moved back and forth in a capillary of transparent fluid to produce a miniature shutter. In both cases voltages of around 1 V are adequate to produce the optical effect in a few milliseconds, and both states are stable. The very small scale of the structures ensures considerable vibration tolerance, in spite of the use of low viscosity liquids.

It remains to be seen whether these curious physical effects can be developed into cheap and reliable displays with good visual appearance.

VIA MAGNETO-OPTIC DISPLAYS

Two approaches have been discussed in the literature; the first (20) is an extension of magnetic bubble technology, whereas the second, which will be discussed here, has similarities to laser-written magneto-optic storage devices (21, 22).

The display effect is based on the Faraday-rotation of polarized light in magnetic domains in transparent magneto-optic materials. In general, when polarized light passes through the material its plane of polarization is rotated. The ideal situation produces a 45° clockwise rotation with one direction of magnetization, and a corresponding 45° anti-clockwise rotation with reversed magnetization. When viewed through a correctly orientated analyzer the transmission of the combination can be switched between maximum and minimum values.

A recently disclosed (22) version of this display used an array of small islands ($\sim 100 \times 100 \mu\text{m}$ square, $\times 5 \mu\text{m}$ thick) of magneto-optic iron garnet grown epitaxially on a gadolinium gallium garnet substrate as shown in Fig. 6. A combination of heat and external magnetic field was required to reverse the magnetization of the magnetic islands. Temperatures of between 50°C and 60°C combined with fields $\sim 200 \text{ Oe}$ were found to be adequate. For data storage devices the heating is supplied by a focussed laser pulse. In the display case, heating was generated by a minute resistive heater evaporated on the surface of each display element. The magnetic field was also locally generated by current pulses through a grid of conductors on the substrate. A well defined threshold existed for both the magnetic field and temperature, so matrix addressing without cross-talk was readily achieved. To switch a single element required $10 \mu\text{s}$ pulses of heat and field and dissipated $\sim 280 \mu\text{J}$. To switch 10,000 elements per second consumed $\sim 2.8 \text{ W}$, but thanks to the permanent memory of the device the mean power could be much lower.

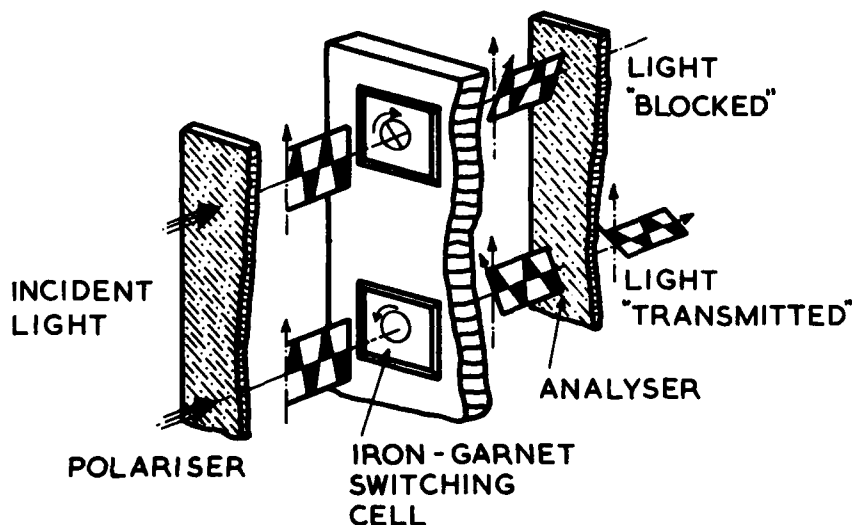


Figure 6. Operating Principle of Magneto-Optic Display Elements.

The largest prototype described (22) contained 256×64 elements on a $3 \text{ cm} \times 0.75 \text{ cm}$ substrate. Because of the small size it was viewed in projection with considerable magnification. Contrast ratios up to 20:1 were claimed, but no data was given on the transmission efficiency of the device. Because of the thermal aspects of the device operation it must be assumed that its temperature range is very limited. At high temperatures (ie above 50°C) the operating effect is lost, whereas at low temperatures the power requirements probably become excessive.

VIB MAGNETIC PARTICLES

Magnetic particles displays consist of a thin layer of permanently magnetized, $200 \mu\text{m}$ diameter, particles, as sketched in Fig. 7. One side of each particle is strongly reflecting and the other side absorbing. Several realizations of this device have been published, but in the preferred version (23) each particle was encapsulated in a transparent micro-capsule with a layer of oil and so was free to rotate according to an externally applied magnetic field. This external field was supplied by a layer of moderate coercivity ferrite powder immediately behind the capsules. The direction of magnetization of the ferrite, and hence the orientation of the display particles, was controlled by an X-Y matrix of current carrying conductors. Thus the conductors could address each element of the display individually, the ferrite particles locally stored the data, and the encapsulated particles rotated to present either their bright or dark sides to the observer.

Display matrices with up to 120×120 pixels and resolutions down to $300 \mu\text{m}$ have been made. Unfortunately, data on the brightness, contrast and angle of view were not disclosed, nor was information on temperature range. It was claimed that to reverse the magnetisation of each ferrite memory required $20 \mu\text{J}$ (3A for $0.5 \mu\text{s}$), but no data on the reorientation speed of the display particles was given. Earlier versions of this device, using less sophisticated construction methods, demonstrated wide viewing angles and contrast ratios up to 15:1. Unfortunately these earlier versions had poorer sensitivity or suffered from particle migration in the plane of the display with consequent non-uniformity of appearance.

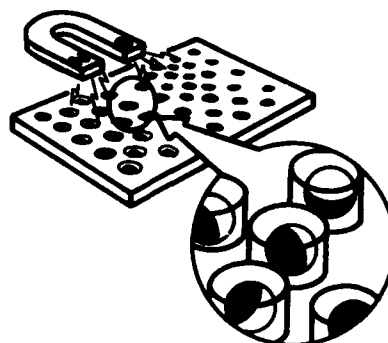


Figure 7. Principles of the Magnetic Particles Display.

VII ELECTRO-MECHANICAL DISPLAYS

In this section several devices are discussed that have used mechanical displacement of reflective films to achieve a display effect.

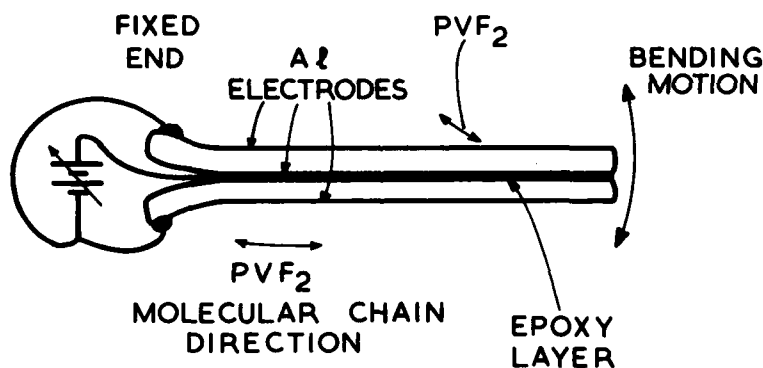


Figure 8. Basic PVF₂ Bimorph Cantilever Structure.

The first (24) used a bimorph structure of piezoelectric polymer films. The basic construction of the bimorph is shown in Fig. 8, where two 9 μ m thick sheets of polyvinylidene fluoride (PVF₂) were stuck together by a thin epoxy layer. Electric fields were applied via thin films of aluminium on the outer surfaces of the sandwich. The electric polarization of the two PVF₂ layers was such that one expanded and the other contracted when volts were applied, causing the whole device to bend. With one end rigidly held, the device behaved as a cantilever. Various rather large display devices have been made with an optically reflecting plate attached at right angles to the free tip of the cantilever. When volts were applied this plate was deflected into or out of the field of view of the observer. In this way viewing angles and contrast ratios were comparable to "plain paper".

One demonstration of this method used cantilevers 2 cm long to produce a 7-segment numeral measuring 16 x 28 cm and still achieved switching times of 32ms with ± 120 V drive. Other smaller displays achieved 21ms switching time, independent of temperature between -37°C and +40°C, with ± 60 V drive. The construction of these demonstrations suggests that high resolution would only be achieved with great difficulty, and there was no suggestion that matrix addressing might be applicable.

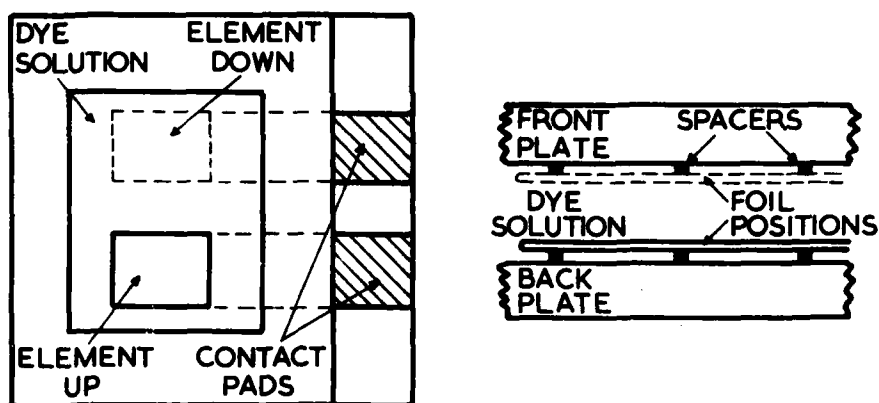


Figure 9. Plan and Cross-Section of the Dye-Foil Display.

Other types of electro-mechanical displays have been described which bear some similarities to electrophoretic displays in that electrostatic forces have been used to move reflecting elements. The simplest was called a "dye-foil" display (25) and is shown schematically in Fig. 9. It consisted of two glass plates bearing the usual transparent conductors, spaced 0.1mm apart and filled with an opaque dye solution. Several thin metallic foil fingers were attached by one end to the lower plate, but were electrically isolated from that plate. The other ends of the foil fingers were free to move in the solution, and could be attracted to either surface by means of AC waveforms applied to the fingers and transparent conductors. An experimental prototype was described in which an elementary bar-graph was composed of 10 fingers, each 0.6 mm wide. On state reflectivity of 80% was claimed with 13:1 contrast ratio and wide viewing angle. Switching time was 0.5s at 25°C, and the device operated from -65°C to +100°C, although the response time at low temperature was not disclosed. Drive voltages of 45 V at 1 kHz were required, but power consumption was only $10 \mu\text{W cm}^{-2}$. No mention was made of multiplex drive.

A more advanced version, called an "electroscopic" display and operating on similar principles has been developed by te Velde (26). As before a metal foil was moved up or down between transparent conductors in a cell filled with dye solution. Two versions were described in which the foil was either totally unattached or was fixed by miniature springs to the lower plate. The mode of operation was similar to that of the dye-foil display, but three essential improvements are evident. Firstly, the manufacturing technology used ingenious etching techniques which defined the foil mirrors, springs, electrical connections etc, in a convenient manner. Secondly, the 200 μm square foil mirrors were perforated by an array of 4 μm diameter holes which permitted rapid fluid flow past the moving foil but did not degrade the on-state appearance. Thirdly, both device configurations showed considerable hysteresis, having well-defined stable states with the foil at either electrode. This hysteresis, with its large threshold voltage for foil displacement, implies long-term memory and the possibility of matrix addressing, although this was not demonstrated. No data on the size and complexity of the prototypes was given.

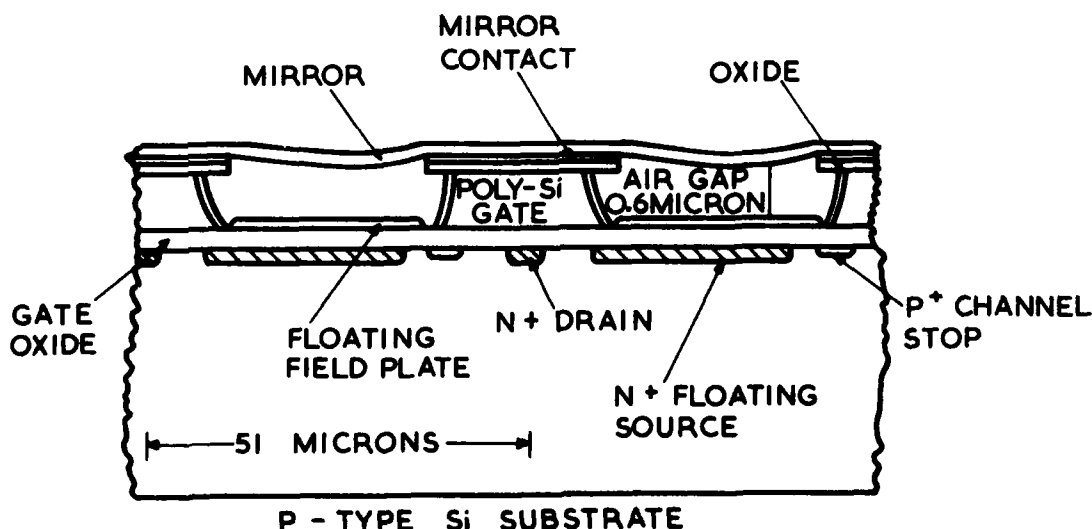


Figure 10. Cross-section of the Deformable Mirror Display.

The final electro-mechanical display is called a "deformable mirror" display (27) and is sketched in Fig. 10. This device is basically a large area silicon integrated circuit, similar to those used in certain LCDs and electro-phoretic displays, consisting of an array of transistors that control the picture points directly.

The surface of the Si slice is covered by an array of air-gap capacitors which constitute the picture points. Each capacitor consists of a lower fixed plate on the Si surface coupled to a drive transistor, and an upper plate made of a sheet of metallized polymer, supported about $0.6\text{ }\mu\text{m}$ from the Si surface by bars of oxide. The mirrors are normally undistorted, but when selected drive transistors are activated (using conventional line-address methods) the corresponding mirrors are distorted by the attractive electrostatic forces. When observed with Schlieren optics, either directly or in projection, good visual contrast is obtained between distorted and undistorted mirror elements. The prototype display described by Hornbeck (27) had 128×128 elements on $51\text{ }\mu\text{m}$ pitch, with the deformable mirrors occupying 32% of the total area. Great care had been taken in the device design to ensure that excessive distortion of the mirror film could not cause catastrophic failure. The drain and gate bus-bars of the chip were discretely connected to external decoders and drive circuits, although in principle these circuits could be incorporated in the display chip. The display was driven from +28 V and -15 V voltage rails, and response times were about 25 μs . Data storage times were $\sim 200\text{ms}$, permitting data refresh at TV frame rates without significant loss of contrast.

The contrast ratio of 5:1 was significantly limited by the low active area ratio. The prototype contained a number of defects, both bus-bar faults, permanently "on" and permanently "off" elements, amounting to some 6% of the total. It was concluded, however, that process improvements should reduce defects to $<0.5\%$.

VIII SUMMARY AND CONCLUSIONS

It appears from the foregoing sections that there are many new and ingenious display techniques that are worthy of serious consideration. In the attempt to see the relative merits of these techniques more clearly, Table 1 has been compiled from a selection of the studies referred to earlier. The entries in the table all refer to performance actually achieved in the references quoted. Some of the papers referred to make predictions of performance that might be achieved with further research and development, but such figures have not been included since they are necessarily based on assumptions that may not subsequently prove justified.

The choice of papers for inclusion in this table has been based on a rather subjective assessment of either the overall best performance achieved, or the best documented performance. This choice has been somewhat arbitrary, and in some cases better values for particular performance parameters have been achieved in other papers.

We should now look more closely at the table to assess relative performance and attempt the objective comparison with LCDs referred to in Section I.

Dealing first with visual appearance, two omissions from virtually all assessments are notable, namely, measured values for either the brightness or angle of view of the displays. Although enthusiastic, subjective assessments are often made, it is a rare paper that quotes measured values. While it is obvious that the restricted angle of view of twisted nematic LCDs should be considerably surpassed, measurements of the variation of either brightness or contrast with viewing angle are rarely found. To be fair, of course, it is hard to find such data for LCDs!

Measurements of visual contrast at normal incidence for monochrome displays are rather easier and are often quoted, although the illumination conditions are rarely stated. In some cases it is possible to trade contrast against response time, and it appears that all displays listed can achieve adequate contrast for the display of alphanumeric information. In general, the grey-scale capabilities of these devices have not been investigated, although most should have some scope for grey-scale. To achieve adequate grey-scale for video applications, however, requires a large maximum contrast value, and it is clear that some of the devices quoted would need considerably higher contrast before this might be considered. Only two of the devices listed were restricted to use in projection only, the majority of others being viewed in reflection, with a few having the capability of either mode of operation. It should be especially noted that the lutetium diphthalocyanine ECC display is the only approach showing a multi-colour capability. It is not yet clear, however, how this property may be harnessed in complex displays, nor how it may best be utilised.

On the topic of response speeds, the values quoted are generally those pertaining at around 20°C . Many devices gave response speeds in the same range as LCDs, only the magneto-optic and deformable mirror devices giving really significant improvements. In most cases little information was given about the variation of response speed with temperature, one notable exception being the silver electroplating display (1), where operation to -40°C at constant writing speed was achieved.

Considering drive requirements next, it should be noted that most of the prototypes required less than 15 V drive, the maximum value for cheap, low-power, integrated circuits. Only the electrophoretic devices required considerably higher voltages, but those high voltages only resulted from the need for 20ms response times.

The calculation of current and power requirements is complicated by the fact that the majority of these devices have significant built-in memory. Thus, although quite large currents may be needed for short periods to change the displayed information, the mean dissipation can be very low provided that the information is changed only occasionally. It must be remembered, however, that the supply of short pulses of high currents may not be as easy as the nearly continuous provision of very low currents.

The intrinsic memory of so many of these devices may have further importance, particularly when displayed information must be retained during interruptions of power supplies and when data is changed very infrequently.

A wide range is apparent in the maximum number of elements that can be addressed. The first point to make is that only one of the prototypes listed, the electrophoretic display of Chiang (14), had any matrix addressing capability intrinsic to the display effect, and this required 80 V pulses for satisfactory operation. The remaining prototypes fall into two classes: those that were suitable for low complexity, direct drive applications such as 7-bar numerics; and those of higher complexity where the matrix addressing capability was a property of the rather complex substrate. This included devices on large area Si MOS substrates and one on a "Varistor" substrate - two techniques already shown to be applicable to LCDs. The two high resolution magnetic displays also required highly complex substrate structures, with the added disadvantage of high current drive pulses. It seems unlikely, therefore, that any of these approaches are capable of significantly simplifying either the construction or drive requirements of large area, high resolution displays, beyond the level already achieved by LCDs.

The final point, that of lifetime, is largely unknown. Although 10^7 write/erase cycles sounds impressive, it should be remembered that a clock display indicating seconds performs over 3×10^7 operations per year.

In conclusion, therefore, we have seen that many novel approaches exist to the problem of providing flat panel displays. No doubt many more alternatives will be suggested in the near future. Many show considerable promise, but at present none stands out as a clear challenger to the established LCDs for the full range of applications envisaged. Many of these approaches, however, do show advantages when only a restricted specification is considered. It may be in visual appearance, speed at low temperatures, the desire for "all solid" construction, the provision of long-term memory, etc. It remains to be seen whether these special challenges can be met by innovation or improvements in the performance of LCDs, or whether various of these alternative approaches can capitalise on their advantages and overcome their weaknesses.

Type and Reference	Electro-plating		Electro-chemi-chromic		
	Silver (1)	Viologen (4)	WO ₃ (6)	Ir Oxide (12)	Lu Dipth. (10)
Size	-	2.5x2.5cm	0.5 cm	7.5 cm	-
Number of Elements	-	64 x 64	7-bar	7-bar	7-bar
Contrast	4:1	-	2.5:1	2:1	Multi-colour
Direct View or Projection	Direct	Direct	Direct	Direct	Direct
Voltage	1	-	<1	±1	±1.2
Current/charge	<1mA/mm ²	<5mA/mm ²	4mC/cm ²	30mC/cm ²	-
Memory?	10 min	Memory	48 hrs	Memory	Memory
Matrix Address	No	Yes	No	No	No
Active Substrate	No	Si FETs	No	No	No
Operating T-range	-40 to +80	-	-	? to +70	-50 to ?
t _{ON}	100 ms to 300 ms	4 ms	0.9s	20 ms	<20 ms
t _{OFF}	300 ms	20 ms	0.9s	20 ms	<20 ms
Liquid/Solid	Liquid	Liquid	Solid	Liquid	Liquid
Complexity	Simple	Complex	Fairly Simple	Fairly Simple	Simple
Lifetime	> 1 year 10 ⁷ cycles	-	> 3 years > 10 ⁷ cycles	- > 10 ⁷ cycles	- 5 x 10 ⁶ cycles

Type and Reference	Electro-phoretic		Suspended Particles (18)	Magneto-Optic (22)	Magnetic Particles (23)	Deformable Mirrors (27)
	Direct Drive (14)	Varistor (16)				
Size	2.5x2.5cm	2.5x2.5cm	-	3 x .75cm	4 x 4cm	6.5x6.5mm
Number of Elements	32 x 32	32 x 32	-	256 x 64	120 x 120	128 x 128
Contrast	-	-	10-30 in Projection Either	20:1	15:1	5:1
Direct View or Projection	Direct	Direct		Projection	Direct	Projection
Voltage	<80 V	±70 V	<10 V	15 V	3 V	30 V
Current/Charge	-	100mC/cm ²	-	1.5A for 10 μs	3A for .5 μs	-
Memory?	Memory	Memory	Refresh	Memory	Memory	Refresh
Matrix Address	Yes	Yes	No	Yes	Yes	Yes
Active Substrate	No	Varistor	No	No	No	Si FETs
Operating T-range	-	-	? to +85°C	? to +50°C	-	-
t _{ON}	> 20ms	20ms	100ms	10 μs	-	25 μs
t _{OFF}	> 40ms	20ms	300ms	10 μs	-	25 μs
Liquid/Solid	Liquid	Liquid	Liquid	Solid	Lubricated Solid	Solid
Complexity	Simple	Complex	Simple	Complex	Complex	Complex
Lifetime	-	-	-	-	-	-
	-	-	>10 ⁵ cycles	-	-	-

Table 1.

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OPTICAL TECHNIQUES FOR AIRBORNE DISPLAYS

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1 INTRODUCTION

Most electronic displays, whether used in aircraft or in a multitude of other applications in homes, offices, industry and elsewhere, are designed to be viewed directly, and it is only because of some particular need that optical elements are placed in front of the display so that the display is viewed through them. In the case of aircraft displays, it is of prime importance in most multi-crew aircraft that the displays should be seen by more than one member of the crew, and hence from a range of head positions. This effectively prohibits the use of optical elements, apart from those of zero power (filters), except in the case of single-crew or tandem-seated military aircraft. In such military aircraft there can be very important reasons why displays with optical elements may be used, although there are typically only one or two of such displays for each crew member, the majority of displays being viewed directly in the conventional way.

This paper does not attempt to describe in detail the optical designs used in airborne electronic displays, but rather to indicate in broad terms the different types of optical systems used, and the design constraints which apply to them. Because there are several types which differ quite fundamentally in their design arrangements, examples of all the principal types are given in section 3. Of particular interest is the use of diffractive, rather than the conventional refractive, optics in the types of head-up display described in section 3.5; this is one of the few examples of new technology in optics (excepting electro-optics) in recent years.

2 CLASSIFICATION AND SPECIFICATION OF OPTICAL SYSTEMS

Optical systems used in conjunction with airborne displays can usefully be classified according to their function, as follows:

- (i) For the rejection or minimisation of unwanted light which will confuse the view of the display. Sunlight rejection is the usual requirement, and is frequently accomplished by the use of filters (see section 3.1 below), although elements with optical power may also be used (eg see section 3.3).
- (ii) For magnification and/or collimation. This is the classical use of conventional optics, in which the object plane lies on the display device and the image plane is positioned at some convenient distance from the observer, a magnified image of the display being seen.
- (iii) For the combination of two or more separately-generated images. This is generally achieved by the use of a plane combiner within a lens system, and can be used for combining either similar or dissimilar optical images.
- (iv) For the superposition of a display image over a direct view of the outside world.

In many instances airborne displays use a combination of these functions, and the head-up display is probably unique in that most designs contain examples of all four functions.

Two further techniques may be mentioned, those which amplify the light intensity of an image, and those which transform it from one wavelength to another. Although they are found in a type of display system now frequently used in military aircraft cockpits, the night vision goggle, they are not considered further in this paper which is entirely devoted to passive optics of refractive and diffractive types.

The designer of a complete electronic display system incorporating optical elements will agree an overall display system specification with his customer, together with a separate specification for the optical module, since the latter is normally produced by a specialist manufacturer. This subsystem specification will contain design requirements for two distinct sets of parameters.

The first set defines the optical characteristics. As shown in Fig 1 this will include the position and size of the object and image planes, and an exit pupil which will be of particular importance in excluding rays outside it. A range of eye positions will be specified over which there will also be requirements for field-of-view, image quality, which will probably include positional accuracy and distortion, efficiency and vignetting, and resolution. Modulation Transfer Function (MTF) is sometimes specified and is particularly useful as it can be combined with the MTFs of electro-optical elements such as CRTs to give an overall system MTF. Many of the parameters which define image characteristics are functions of the wavelength of the light and hence their specification becomes extremely complex.

The second set of parameters is more concerned with constraints on the hardware. Typical of these are size and mass, but the positioning of the module envelope within the optical diagram may also be important, particularly in the case of the distance of the design eye position relative to the nearest optical element - usually called the eye relief. The relative significance of all these parameters depends strongly on the particular application, and will be referenced in the specific examples which follow.

3 SPECIFIC EXAMPLES

3.1 Optical filters

In airborne displays, use is frequently made of filters, ie optical elements which have no optical power and do not affect the imaging characteristics of the display, but influence the amount of light emerging from the display, or entering the display from the cockpit. Their function is to improve the contrast of the display in the presence of bright ambient lighting, particularly sunlight.

Fig 2 shows the use of a filter in front of a head-down electronic display such as a CRT. Ambient light of intensity I_1 is incident upon the filter and display; suppose it is successively attenuated by factors of A_1 when passing through the filter, A_2 when reflected or scattered at the display surface, and A_3 when re-passing through the filter. Then the emergent light has intensity given by

$$E_1 = \frac{I_1}{A_1 A_2 A_3}$$

where A_1 , A_2 and A_3 are all greater than unity.

Light which originates at the display, and which emerges at the same angle as the ambient light, emerges from the filter with intensity given by

$$E_2 = \frac{I_2}{A_4}$$

where A_4 may differ from A_3 because of wavelength differences between the ambient and emitted beams.

To improve the contrast ratio of the display in these ambient conditions, it is desirable to maximise E_2/E_1 .

$$\text{where } \frac{E_2}{E_1} = \frac{I_2}{I_1} \frac{A_1 A_2 A_3}{A_4}$$

Clearly both A_1 and A_2 should be as large as possible, but unfortunately A_2 is often small, since with a CRT the white phosphor powder has a diffusing surface with a high scattering coefficient. A_1 cannot be made very large because A_1 and A_4 are usually closely related, and large A_4 values would result in a very dim display, even though it would have high contrast, and also the effect of specular reflection would become more noticeable.

Three cases can be considered. Firstly a useful gain can be obtained with $A_1 = A_3 = A_4$, because contrast can be increased by attenuation if some loss of display luminance is acceptable. A filter having approximately uniform attenuation over a range of angles and of wavelengths, usually called a neutral-density filter, provides this condition; attenuation of up to 10 can be used but around 2 is more general in cockpits.

The second case is with $A_1 > A_3 = A_4$. A difference in attenuation between the incident ambient light and the emergent light can be provided by a filter having characteristics which are a function of the angle of the beam of light passing through. This is generally arranged by means of a fine mesh buried in the filter, so that light passes through tunnels when at a certain angle, but is absorbed at other angles. These angular characteristics can be matched to the display geometry, so that incident sunlight is largely absorbed whereas the display light, as seen by the aircrew, is relatively unattenuated. Filters based on multiple-layer interference patterns also have angular attenuation characteristics, which can be very sharp, but have not found much favour because they tend to reflect rather than absorb light, and because their wavelength-dependence is sensitive to the angle of view.

The third case is with $A_1 = A_3 > A_4$. This can be achieved if the display is relatively narrow band, and the filter has a pass-band which closely matches the display emission but has high absorption at other visible wavelengths. Fig 3 shows a typical optical filter matched to a P-43 CRT phosphor. For multi-colour displays, it becomes difficult to manufacture a filter having three narrow pass-bands matching three separate phosphor wavelengths, but filters of this type are now being offered to display designers.

Mention should be made of circular-polarising filters. These are often incorporated into other filters in order to attenuate light which has undergone specular reflection at the optical surfaces, and they also act as neutral density filters since they necessarily

absorb at least 50% of the light emitted from the display. Filters usually also incorporate multilayer anti-reflection coatings, and an abrasion-resistant surface coating.

3.2 Biocular magnifying displays

The simplest type of display system incorporating refractive optical elements is formed of a lens or lenses, having positive optical power, through which the electro-optic display surface is viewed. As seen from Fig 4, the design is generally arranged to give a magnified image at a distance from the eyes significantly greater than the distance to the object plane. In some cases the image plane may be at infinity, ie the display is collimated, so that the eye does not have to re-focus when transferring from the real outside world to the display, and some protection against image degradation caused by vibration is also provided.

The relationship between magnification and image distances may be calculated by simple lens theory. Of particular interest is the effect on the display fields-of-view of the 'porthole' formed by the collimating lens, whose diameter is constrained by the practicabilities of cockpit geometry. The two separated eyes of the pilot each have an instantaneous circular field which, for a collimated image plane, has an angular diameter,

$$F_V = 2 \tan^{-1} \frac{D_C}{2d_E}.$$

The fields of the two eyes taken together have the shape shown in Fig 4b; the horizontal field-of-view being elongated and having magnitude

$$F_H = 2 \tan^{-1} \frac{D_C + D_E}{2d_E}.$$

It is usual to try to arrange the value of overlap between the fields of the two eyes such that F_H/F_V is in the range 1.4 to 1.7. This provides an overlap of reasonable magnitude so that the images in the two eyes fuse together and has the further advantage that the rectangular approximation to the total field is then close to a television format. Taking this range of ratios and substituting into the field equations gives, for reasonably small angles, the approximate equation

$$D_E = (0.4 \text{ to } 0.7) D_C$$

which for a typical eye separation D_E of 65 mm approximates to $D_C = 160 \text{ mm to } 80 \text{ mm}$. This range of optical element sizes is therefore required in this type of biocular display, and also in the optically similar simple head-up displays described in section 3.5.

The total field of the display is defined as the envelope of all fields which can be seen by the eye from any position in its normal plane. It is not a function of size of optical element, but is determined by the diameter of the display device and, for a collimated image, is

$$F_T = 2 \tan^{-1} \frac{D_D}{2d_D}.$$

It is generally arranged that F_T is slightly larger than F_H , and hence considerably larger than F_V , so that to see the total field the head has to be moved appreciably more in the vertical direction than in the horizontal. Whether or not this is necessary depends in turn upon whether the whole surface of the CRT or other display device is used to present information.

Simple displays of this type have been used in a few modern combat aircraft, but not as frequently as head-up displays which are derived from them. An example is the Hughes Virtual Image Display shown in Fig 5. This has a CRT display with usable diameter approximately 20 mm, a magnifying lens (actually formed of several elements) of approximately 70 mm diameter, with the image 1.2 m from the design eye position. The instantaneous field-of-view has maximum dimensions $18.4^\circ \times 11^\circ$.

3.3 The 'COMED' Combined Map and Electronic Display

Many modern military aircraft use map displays which are coupled to their navigation equipments so that the maps are moved automatically as the aircraft proceeds on its mission. The Ferranti 'COMED' display incorporates a film-strip map which is projected on to a screen, together with a CRT on which a number of alternative formats can be displayed, the two being combined optically and viewed as a combined single display by the pilot. This arrangement allows flexibility in annotating the map, via the CRT, with information appropriate to the tactical mission.

The optical system as described by Boot¹ has two of the primary functions listed in section 2. These are:

- (i) preventing ambient light, which in the military environment could fall on the surface of the display, from reaching the map imaging screen or the CRT and degrading the image contrast;

(ii) combining the map and CRT images.

The general arrangement of the display is shown in Fig 6. The film-strip map is projected on to a diffusing screen using a conventional but very accurate optical lens module. This screen and the front phosphor screen of the CRT are orthogonal and equidistant from the semi-reflecting pellicle mirror which acts as a combiner, and hence for optical design purposes the subsequent lens assemblies can be designed as though a single object source were located at the CRT face.

The relay lens forms a combined image of the CRT and the map in a plane at the front of the display. At this point it could be viewed (with the aid of an imaging screen) by the pilot from the eye position shown. However such an arrangement would have two disadvantages: the luminance of the image would be very weak, since much of the light would be scattered over a wide solid angle, and in addition the system would be very susceptible to incident sunlight over a wide range of angles which would fall on the imaging screen with a subsequent severe degradation in contrast. To overcome these problems a field lens replaces the imaging screen in the plane of the combined image. Because of this choice of position it has virtually no effect upon the size and quality of the image as seen by the pilot, but it directs the light from the projected image into a restricted beam from where it passes through a well defined exit pupil. The two advantages of this configuration are that direct viewing of the map image and CRT image results in a subjectively very bright image, and because the pilot's head fills the exit pupil, there is no way in which direct sunlight can penetrate the display to fall on either the map imaging screen or CRT and degrade the contrast.

Fig 7 shows the optical arrangement in more detail. It will be seen that the simple relay lens of Fig 6 is realised in practice by two complex groups of lenses, which have to be supplemented by field flattening lenses in front of the CRT and map screen. The field lens is made as a Fresnel lens of relatively low optical quality since the image is not directly distorted by it. The front assembly also includes a contrast enhancement filter and a prismatic screen which slightly elevates the exit pupil relative to the display centre-line.

3.4 Head-up displays with conventional optics

The fourth classification of display optics listed in section 2 has the function of superimposing a display image over a direct view of the outside world. This type of display system is used when it is necessary for the pilot to obtain information while simultaneously viewing the real world, and frequently also when the pilot requires to align some displayed symbology with the real world. In both cases it is necessary that the symbology be collimated, but in the second case the accuracy of the collimation and also of the symbol positions relative to the aircraft geometry need to be very good. Such a display is usually described as a head-up display and is used in virtually all modern tactical aircraft. In its role as a weapon sight it is the modern counterpart of the mechanical gunsights of World War II and after.

The optical arrangement of nearly all head-up displays in current use has been discussed by Chorley³ and is shown in Fig 8. It will be seen that this is in many respects similar to the simple magnifier arrangement shown in Fig 5 and described in section 3.2, but it incorporates two plane mirrors aligned at about 45° to the optical axis. The uppermost of these is partially reflective so that the pilot can see the view ahead through it, together with the reflected symbology. However, the optical characteristics described in section 3.2 are equally applicable to these head-up displays, and result in fields-of-view as shown in Fig 8 which are of generally similar shape to those in Fig 4. It is arranged that the instantaneous field-of-view is less than the total field, so that the head has to be moved both laterally and vertically to see the total field, the effective porthole of the system being positioned just past the combiner as shown in Fig 8.

Head-up displays of this type have proved to be highly satisfactory in service, but the field-of-view limitations have been criticised and are now becoming a real obstacle to the use of head-up displays for night operation with FLIR sensors and for the aiming and release of agile weapons. As shown in section 3.2, the horizontal and vertical fields-of-view are directly related to the diameter of the collimating lens and to its distance from the eye position. A typical lens diameter is 150 mm, and eye-to-porthole distance 750 mm, which gives vertical and horizontal fields-of-view of about 10° and 15° respectively.

Fig 9 shows in detail the optical module for a display of these dimensions. It will be seen that to achieve the accuracy appropriate for weapon-aiming, typically 1.5 mrad in the centre of the field and 5 mrad overall, the optical lens elements are of considerable complexity. Moreover the simple lens shown in Fig 8 is actually replaced by two lens groups, which reduces aberration and distortion but has the effect of increasing the effective eye-to-lens distance. The problem is rapidly compounded as lens diameter is increased, and optical systems with diameters much above 180 mm become so large and heavy as to make themselves impractical for most applications. The design difficulties are also compounded by the need to insert stand-by sights of a colour different from that of the CRT; these are utilised only when the CRT fails to display the required symbology.

It is possible to move the field-of-view vertically by moving the horizontal position of the combining mirror, or to increase it permanently by providing two mirrors as shown in Fig 10. In this display the effective field is produced by two portholes generated

one above the other. However it suffers from a discontinuity in the attenuation of the forward view which is partially alleviated by grading the reflectance of the combiner in the central region, but which is only perfectly corrected for one head position.

The other main problem with conventional head-up displays is associated with image brightness. Pilots naturally require that their forward vision is not significantly impaired by the combiner glass, and that there is no apparent colour distortion. If the mirror reflection is neutral (ie all wavelengths are equally attenuated), then the percentage transmission and reflection must together add up to less than 100%, so that figures of about 75% and 25% may be chosen as shown in Fig 11, adapted from Ref 4. The low efficiency for the reflected symbol image means that the electro-optic display device, usually a CRT, has to emit four times the light which would otherwise be required, with consequent penalties in power and life. Fig 11 also shows the problem of near-vertical sunlight penetrating the optical system and emerging after scattering.

A third disadvantage of head-up displays which should also be mentioned is that the overall shape of the optical system requires that the collimating lens and lower mirror occupy a part of the aircraft's instrument panel which could usefully be utilised by other important head-down displays.

For many years these limitations of conventional head-up displays have been recognised and, as reported in Ref 2, attempts been made to overcome them. These met with little success until the development of diffractive optics to complement refractive optics allowed display designers a new range of options. This new technique and its application to head-up displays is discussed in section 3.5.

3.5 Diffractive-optic head-up displays

The field-of-view of a head-up display is determined principally by the diameter of the collimating lens and its distance from the eye position, and if the field is to be significantly increased, the diameter of the lens must be increased and/or it must be positioned closer to the eye. The latter can only be achieved if the combiner and the lens are co-located, but the lens is then likely to distort the forward view to the outside world. Attempts to achieve refractive combiners which have optical power for viewing the display, but none when viewing the scene ahead, were largely unsuccessful, but diffractive optics can be used for this purpose provided the real-world scene has a broad spectral content and the display emits very narrow-band light.

Unlike conventional optics, in which rays of light are deflected according to the laws of reflection and refraction which vary only slightly according to the wavelength of the light, a diffractive optic element deflects rays of light through angles which are highly sensitive to wavelength. This is because the diffraction depends on the interaction of the light wavefronts with a periodic structure in the diffractive optical element. The simplest example of such an element is the diffractive grating; when a beam of monochromatic light falls on a grating it is deflected and split so that it emerges as several rays in different directions, the energy in the different beams and the direction of each beam depending on the structure and geometry of the grating. For a 'surface' grating which is produced by ruling or etching lines on the surface of the element, there is considerable energy in many of the diffracted beams, but for the so-called 'thick' gratings, in which the periodicity of the structure is produced by refractive index variations penetrating deep into the material, almost all of the energy is in the primary diffracted beam, so that the grating behaves very much as a prism for monochromatic light. However there is one essential difference; for the grating the deflection angle is determined by the periodic structure within the material and by the wavelength of the light, and not by the surface geometry.

By arranging that the periodic structure in the grating varies continuously along the surface of the grating, light beams will be bent more at one part of the grating than another, and thus may be brought to a focus in a manner analogous to that of a curved mirror or a conventional refractive lens. For diffractive mirrors particularly, in which the periodicity in the material is provided by refractive index variations in planes approximately parallel to the surface, only a very small band of wavelengths such as 10-20 nm will be reflected and focussed, with the remainder of the 400 nm of visible bandwidth being effectively undeflected. Such elements can therefore be used simultaneously as combiners and collimators in fulfilling the design needs described above for wide-angle head-up displays. This configuration of refractive index variations has the further advantage that chromatic aberration is minimised within the 10 nm useful bandwidth.

Construction of diffractive optical elements having these focussing properties depends upon the technique of holography. A hologram of an object, when illuminated with suitable light, appears to generate an image exactly similar to the original object. A special case of this is a hologram of a point source, which if constructed by a parallel reference beam of light and subsequently illuminated by a parallel beam of light along the reference direction will create a point image, ie will produce diffracted beams of light apparently originating from a point source. Hence the hologram of a point source acts as a lens or mirror, and can be used for the head-up display collimator. But just as a simple lens is frequently inadequate to maintain sharp focus over a large image, a simply-constructed diffractive hologram has significant errors over wide fields, which have to be compensated by other optical elements in the display system.

Two alternative methods of constructing a hologram with zero optical power are shown in Fig 12. The back-reflection technique uses the simpler geometrical arrangement of

optical elements and hence stability requirements are more easily met. But the split-beam method provides more flexibility in optical design since the two beams can be focussed and aberrated by different amounts. In either case it can be seen that the gelatin-based material which forms the hologram is illuminated by two intersecting beams of laser light, which set up interference patterns in the gelatin which after processing produce the required refractive index modulations. With the two beams impinging from opposite sides of the gelatin, the interference patterns are approximately parallel to the surface of the gelatin, and the resultant hologram acts as a mirror. As will be seen below, it is useful to use curved diffractive mirrors for some types of head-up display, and these can be constructed by the same optical arrangement; they generally result in smaller chromatic aberration and higher efficiency than plane holograms.

Most holograms for general use are formed on conventional fine-grain photographic emulsion which, following exposure to light and processing, produces variations in optical density in the hologram. The transparent holograms which are required for head-up displays must be formed of refractive index variations, for which purpose the gelatin must be sensitised by some suitable material, of which the only one in common use appears to be ammonium dichromate. As reported by Swift⁴, the complete manufacturing process is complex and not yet fully understood, but in summary it involves:

- (i) coating the substrate with gelatin;
- (ii) sensitising the gelatin with ammonium dichromate;
- (iii) exposing to the interference fringe pattern;
- (iv) processing;
- (v) baking to remove water from the gelatin;
- (vi) encapsulating.

By comparison with conventional photographic techniques, this process is difficult and only recently has it become sufficiently well established to be considered suitable for full-scale production. Exposure times tend to be long, and to maintain optical path-lengths accurate to a fraction of a fringe over relatively long periods requires great care to establish mechanical and temperature stability. Variation in the water content of the gelatin produces corresponding variation in refractive index and hence in the diffraction wavelength, and has to be critically controlled in manufacture and subsequently protected from variation in use by encapsulation. Also cleanliness is particularly important because scattering from small particles will result in unwanted fringes and degradation of optical performance.

The quality of optical element which can now be produced by these techniques is excellent. Fig 13 shows the spectral transmission through a sample; this has a notch of about 20 nm which is diffracted, and a transmission across the rest of the spectrum of better than 90%. Even narrower notches can be manufactured, but in practice are of little use in practical HUDs since the variation in direction of beams diffracted at the hologram necessitates a wider band of wavelengths than would be required for a fixed direction. The notch width is established by gelatin thickness, by exposure levels and by processing control in manufacture.

Using optical elements of the type described, wide field-of-view HUDs of several configurations may be designed, in each case incorporating optical power at or near the combiner. These configurations have been reviewed by Banbury⁵. The simplest to understand was also the earliest to be developed; this is the Hughes system shown in Fig 14 which has been flown in Viggen and Jaguar aircraft. Comparison of Fig 14 with Fig 8 shows that although the general mechanical layout of the two HUDs is very similar, the optical arrangement is quite different. This is most apparent in the positioning of the pupils; in the Hughes diffractive HUD there is an exit pupil at the eye position instead of the porthole of the conventional HUD. Because of this exit pupil position there is a large instantaneous field-of-view which is almost equal to the total field, and which applies to both one and two-eye viewing. The total field can be made much larger than for a conventional HUD; for the Jaguar trials a unit having a field of $33^{\circ} \times 22^{\circ}$ was developed.

The principal difficulty in designing a HUD with this configuration arises because of the large off-axis angles at which the diffractive element is used. This results in errors in the positional accuracy of the collimated image, and although these can be corrected in the centre of the field they become significant at the edges. The correction is applied by off-axis geometry in the relay lens and by electrical distortion of the displayed image on the CRT, the former resulting in a complex and expensive optical assembly. The geometry of the display system also requires that the holographic combiner is manufactured using the optical arrangement shown in Fig 12a which adds to the manufacturing difficulties.

Similar wide-field advantages are features of the HUD shown in Fig 15 which has been developed by Marconi Avionics and Pilkington PE for the USAF 'Lantirn' programme. This has been fully described by Hussey⁶, who notes that it is one example of a class of HUDs characterised by having a spherical combiner with its optical axis passing close to the pilot's eye position, the so-called quasi-axial HUDs. Such an arrangement would normally require the CRT to be placed in a totally impractical position close to the pilot's head, but by an ingenious arrangement of mirrors and a relay lens the CRT can be located in the conventional position behind the instrument panel. The mirror nearest to the pilot, the spherical combiner and the eyebrow mirror are all

holographic elements, the first two being arranged at such angles that the light from the narrow-band phosphor is reflected from it when incident at one angle, but passes through unaffected when incident at another angle.

Although this optical arrangement is apparently rather complex as compared with the off-axis type, it has smaller optical errors and the components are generally easier to manufacture. One potential drawback is the presence of the additional mirror and support at the top of the combiner, which may be found obtrusive by pilots. As pointed out by Banbury⁵ in an extensive discussion of wide field HUDs, other configurations of quasi-axial display can be designed, and the choice between these will be made according to the constraints of particular aircraft cockpits. These designs can all be arranged to have an exit pupil close to the design eye position, thus eliminating the 'porthole' of conventional HUDs and providing an instantaneous field closely similar to the total field.

The diffractive HUD also alleviates the luminance problem for conventional HUDs referred to in section 3.4. Fig 13 shows that over the whole visible field there is very little transmission loss, while the displayed image is reflected from the holographic element(s) with an efficiency of about 80%. Although the eye is highly sensitive to small amounts of colouration, the effect of removing a small segment of green transmission has not so far caused adverse comment from most pilots. Indeed, the improved luminance efficiency could be a reason for using diffractive combiners with no optical power in otherwise conventional HUDs.

Although diffractive HUDs are only now becoming established, and only the 'Lantirn' HUDs are yet in quantity production, it appears likely that further applications will follow when the wide-angle and high-brightness requirements justify the weight, size and cost penalties that necessarily result from their use.

3.6 Helmet mounted displays

The HUD mounted on the top of the instrument panel has, even with the widest conceivable fields-of-view for practical optical arrangements, an angular coverage which is only a small part of the total angular field in which the pilot may wish to direct his vision. The canopy of a modern combat aircraft such as an F-16 gives unobscured vision over almost all the upper hemisphere, and some of the lower hemisphere as well, and for some tactical situations the pilot may wish to direct a line of sight to points well outside the field of the HUD.

Moreover for the night operation of both fixed-wing aircraft and helicopters it may be desirable to present to the pilot a video image from an E-O sensor such as FLIR or TV, whilst he is looking outside the field of conventional head-up or other displays. Such displays can only be implemented if they are carried on the pilot's helmet so that they are effectively aligned to his head position. The operation of such displays generally requires that the angular orientation of the helmet relative to the airframe be measured, and this measurement may in turn be used to control the pointing of the E-O sensor; the operation of complete systems incorporating helmet-mounted displays has been discussed by Shepherd⁷ and by Beyer et al⁸. The elements of a helmet-mounted display are shown in Fig 16. It will be seen that it is in essence a miniaturised HUD, the pilot being able to view the displayed information collimated to infinity and superimposed upon his view of the outside world. As with conventional HUDs, it is fairly easy to design the optical system provided the field-of-view is relatively small, but the problems rapidly become difficult as this is increased. Helmet-mounted displays thus tend to divide themselves naturally into two classes, those which are used for sighting purposes only (often referred to as helmet-mounted sights) in which the field-of-view can be kept small, the displayed information simple, and the whole assembly relatively light, and those which are used to display video information using a CRT, with larger fields-of-view, and having a significantly greater mass.

The design parameters for helmet-mounted displays are very different to those for HUDs. It is virtually impossible to design an acceptable helmet-mounted display which can be seen by both eyes, so that all practical designs appear to have been monocular. The eye position box referred to in Fig 1 is therefore the total range of positions of a single eye relative to the display, and ideally this can be large enough to cover all variations in the head/helmet geometry of individual aircrew. However in some designs it is necessary to adjust the display to match the individual, and the box has to be large enough to accommodate only variations during flight, which can be caused by movement of the helmet on the head and can be quite large.

Fig 17 illustrates a typical optical design incorporating a relay lens. D_E is the diameter of the exit pupil, D_C that of the collimating lens, and d_R the distance from lens to eye, which may need to include a combiner mirror. Then for a field-of-view $2A$

$$D_C = 2d_R \tan A + D_E.$$

For wide field-of-view displays with good tolerance to eye movement and good eye relief, d_R , A and D_E all need to be large, but to keep the weight and obscuration to acceptable levels D_C must be fairly small. The difficulties in finding an acceptable compromise are apparent from the above equation and are further discussed below.

An important design constraint is to minimise obscuration of the pilot's normal view; this applies not only to his forward vision through and near the combiner glass, but also to his peripheral vision which can be important even though it is not critical. Finally there is the very important parameter of mass, since excessive mass on the helmet, especially if it is asymmetrical, can create both safety and fatigue problems.

A typical sight design, as developed by Marconi Avionics, is shown in Fig 18. Because of the limited field-of-view, a relatively long optical path from collimator to eye is possible, and this particular arrangement allows a large exit pupil (16 mm) to be formed at the pilot's eye. The use of an LED display element allows the whole assembly to be packaged neatly into the helmet, and the spherical combiner element can be fabricated integrally with the visor. Although the combiner is operating with large off-axis angles, a sight of this type can have an optical accuracy better than the ability of the pilot to place the sight over a target, even though the optical arrangement itself is very simple.

The wide field-of-view display is much more difficult to design, and many alternative arrangements have been tried in an attempt to find a reasonable compromise between size and weight, field-of-view, exit pupil and eye relief. These designs have been reviewed by Bridenbaugh et al⁹ and by Task et al¹⁰, and an in-depth discussion of the problems and of one particular line of approach has been published by Fehr¹¹, who also describes the detailed optical designs evolved. It appears that the concept of using optical power at the combiner, in some cases by use of the helmet visor, has been abandoned and the only wide field-of-view display which has been taken to operational status has a conventional plane combiner, together with spherical lens elements in both the collimator and the relay lens. This is the Honeywell IHADSS (Integrated Helmet and Display Sighting System) adopted for the US Army AH-64 Helicopter, and described in Ref 9.

An alternative approach by Ferranti is to accept that for large fields of view the distance d_p from lens to eye is insufficient to allow the use of a combiner, and hence the direct view of the outside world from one eye must be lost. A helmet-mounted display with $40^\circ \times 30^\circ$ field-of-view, 15mm exit pupil and excellent eye relief has been developed and has been extensively tested, but the operational acceptability of this solution remains to be proven.

It is possible to use the techniques of diffractive optics described in section 3.5 above for helmet-mounted displays. Early work in this area which was reported by the USN Naval Weapons Center¹², related to narrow field-of-view sighting systems. Wide field-of-view displays were investigated by the Hughes Aircraft Company, who reported in 1974¹³ on the results of their preliminary studies and experiments, but there appear to have been no published reports of more recent developments in this field.

3.7 Multicolour displays

The conventional technique for producing multicolour electronic displays is to generate patterns of different colours at the surface of the electro-optic display device, eg a shadowmask or penetration type of CRT. But these devices have been difficult to develop to the standards appropriate for use in military aircraft, and optical techniques have, therefore, been proposed for use in combination with simpler display devices as part of multicolour airborne displays.

In 1975 Shanks¹⁴ proposed the use of a single CRT, with a broadband white-emitting phosphor which was addressed frame-sequentially with patterns appropriate to different colours. In front of the display was a nematic liquid crystal filter, switched in synchronism with the CRT frames, to form a coloured filter having successively two or more monochrome pass-bands. Prototype models were produced which demonstrated the practicability of the technique, which is, of course, equally usable with a range of electro-optic display types. No airborne displays have been developed using this technique, probably because of production difficulties with the large LCD filters, and because of the non-standard frame-sequential addressing which creates problems of compatibility with other displays.

An alternative and conceptually very simple technique is to combine the outputs from two or three monochrome displays by optical techniques. The method was proposed by Hunt¹⁵, but has the disadvantage of a large and rather complex mechanical construction, as shown in the similar 'COMED' display described in section 3.3. However it is reported that an airborne display using this principle and incorporating a holographic combining system, is under development in Sweden.

The future for multicolour displays using these optical techniques is not clear, and depends very much upon the progress made in developing CRT's and other display devices with integral multicolour capability and with performances to match the airborne requirements.

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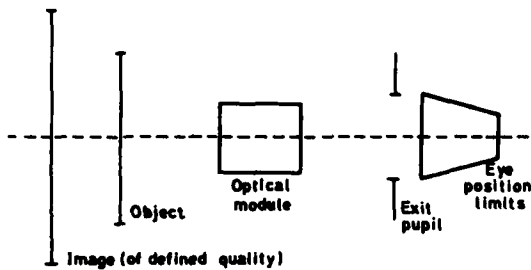


Fig 1 Specified parameters in display optics

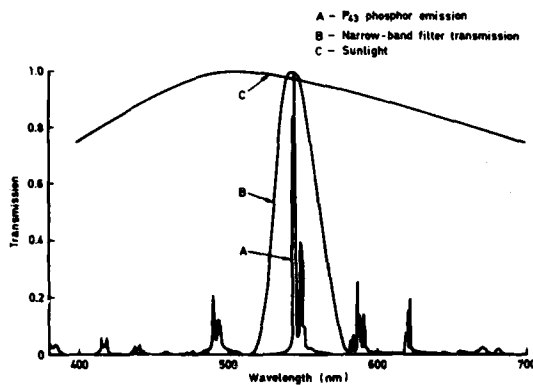


Fig 3 Spectral characteristics of phosphor and filter

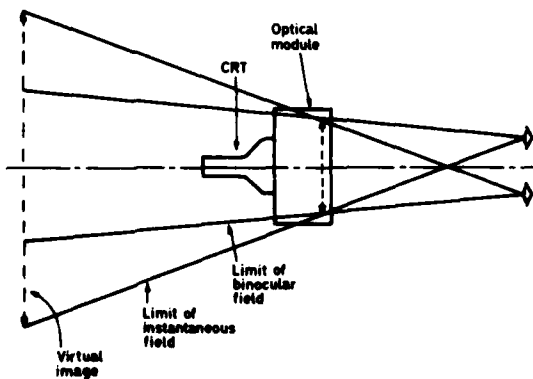


Fig 5 Hughes biocular magnifying display

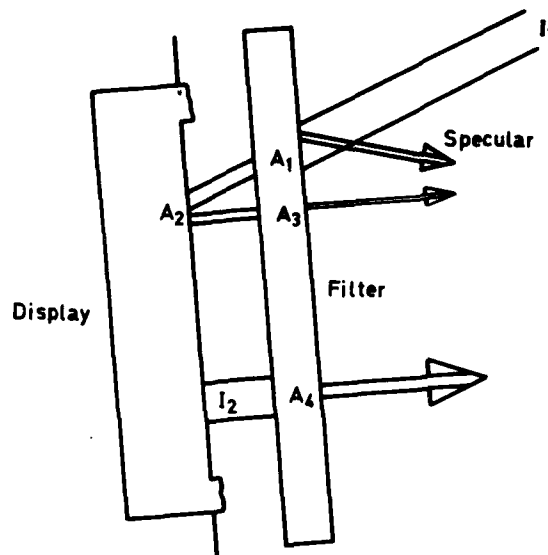
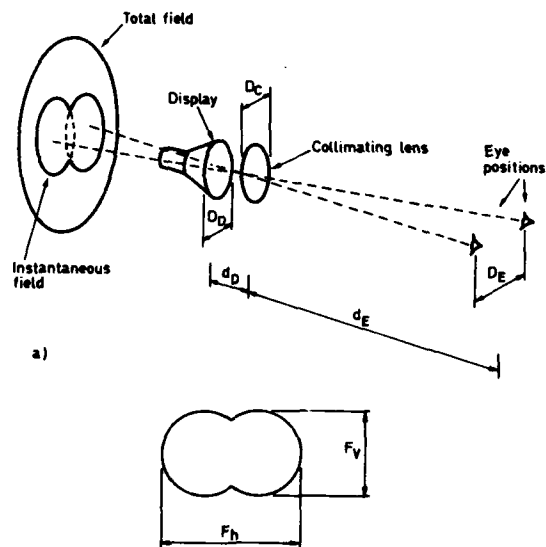


Fig 2 Contrast-improvement filter



a)

Fig 4 Geometry of a simple biocular display

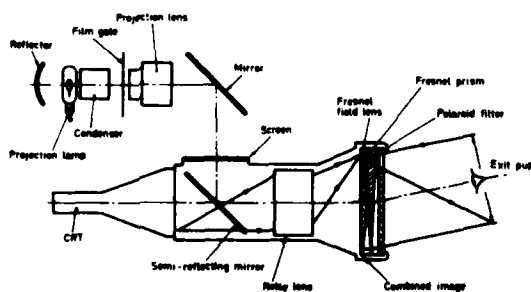


Fig 6 General arrangement of 'comed' display

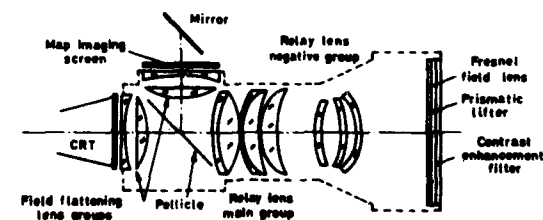


Fig 7 Optical arrangement of 'comed' display

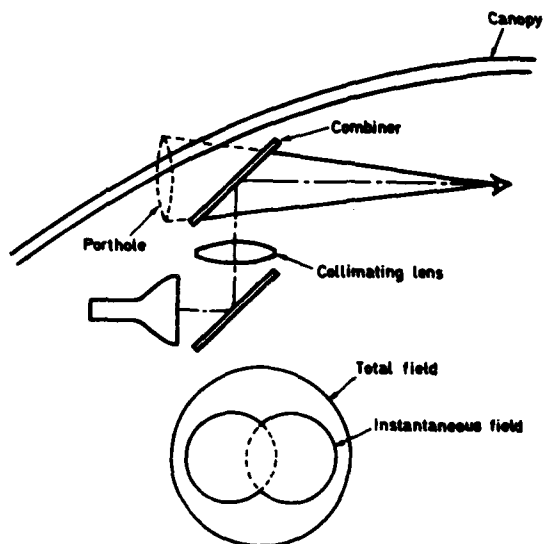


Fig 8 General arrangement of conventional head-up display

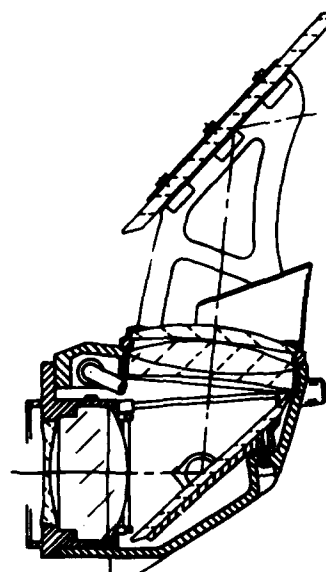


Fig 9 Optical module of head-up display

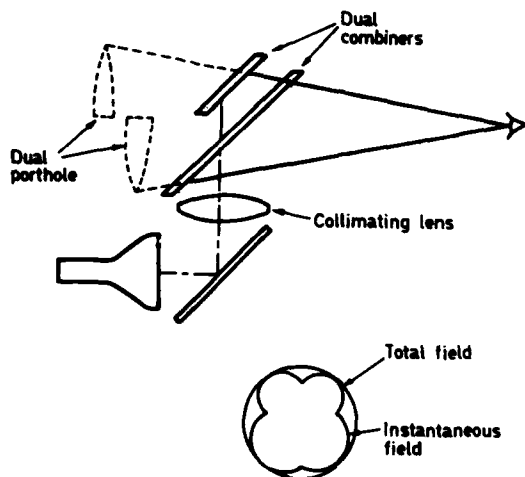


Fig 10 Optical arrangement of dual-combiner HUD

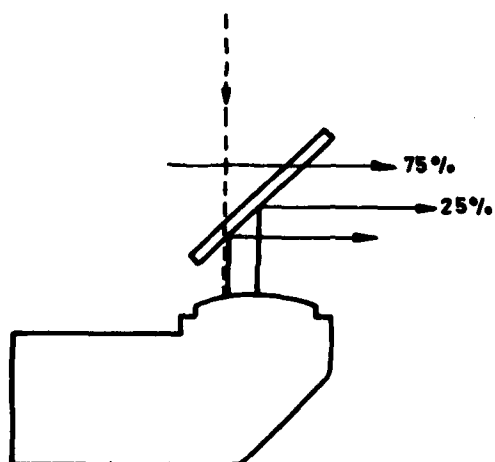


Fig 11 Luminance and attenuation in a conventional HUD

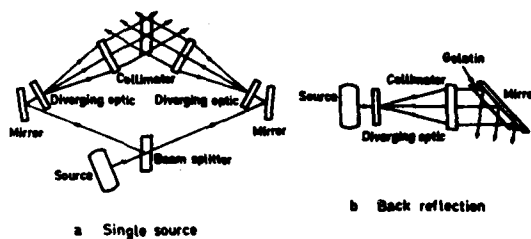


Fig 12 Methods of hologram construction for diffractive optical elements

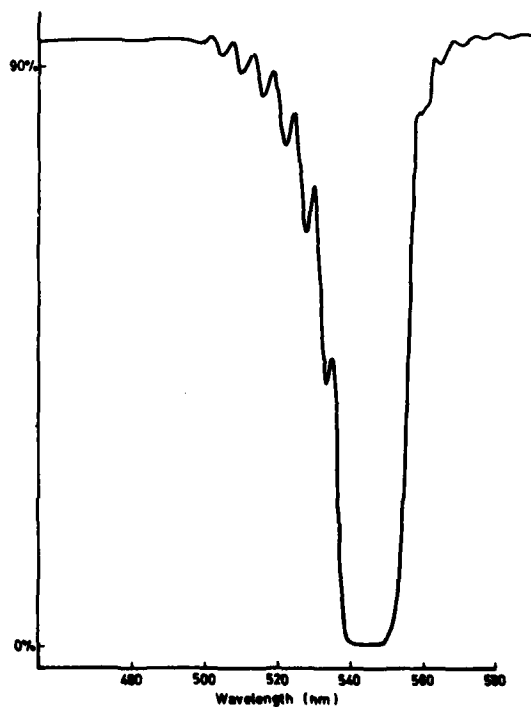


Fig 13 Transmission characteristic for a typical diffractive combiner

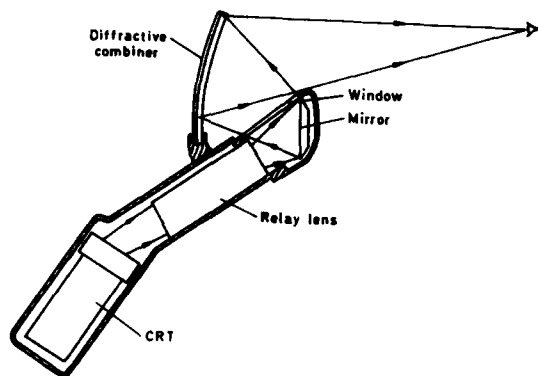


Fig 14 General arrangement of Hughes diffractive HUD

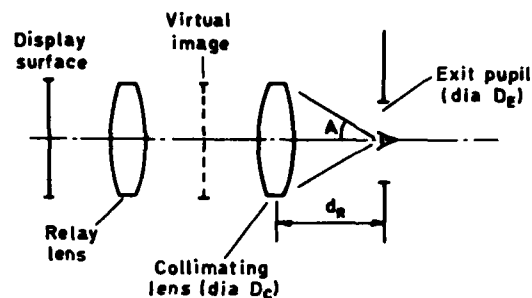


Fig 17 Optical design constraints for a helmet-mounted display

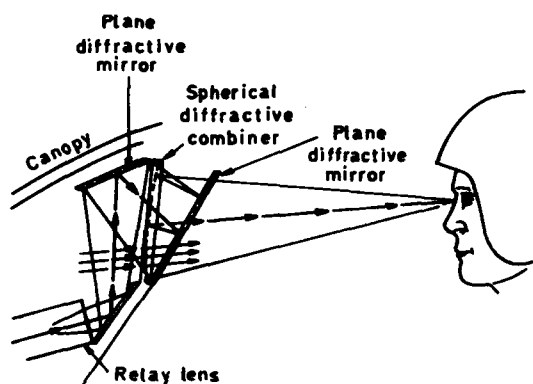


Fig 15 Arrangement of 'Lantirn' diffractive HUD

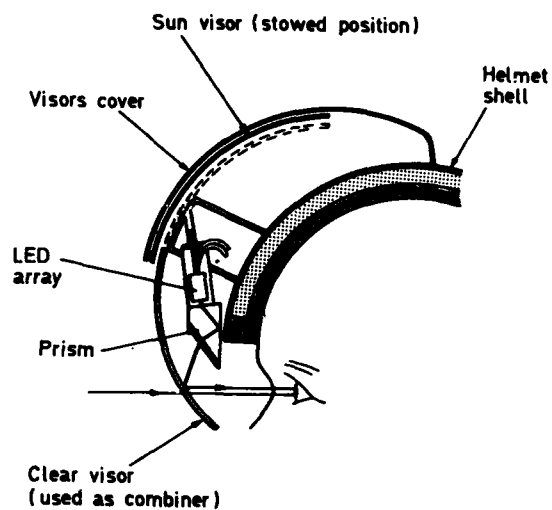


Fig 18 Arrangement of narrow-field helmet-mounted display

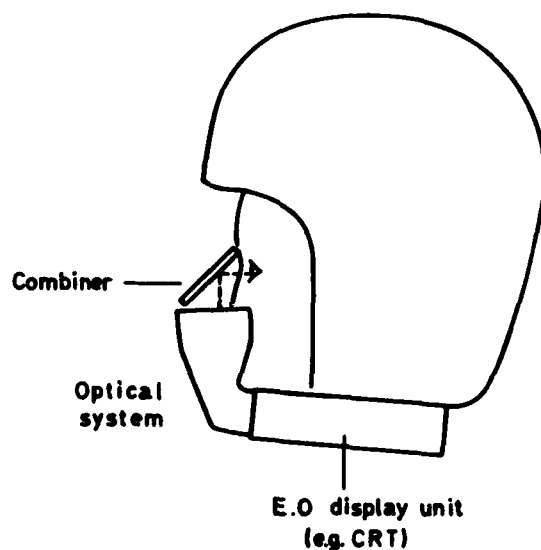


Fig 16 General arrangement of a helmet-mounted display

APPLICATIONS

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SUMMARY

Reproduced here is the assessment chapter of the report of the AGARD Avionics Panel Working Group on Modern Display Technology. Relative comparisons are made among the competing display technologies. Performance measures selected for the comparison are summarized. A matrix of performance measure against technology is generated. Advantages and disadvantages not already evident from the matrix are listed. The relative importance of the performance measures are discussed in connection with the applications described in the Cockpit Environment lecture. Finally an assessment of the potential of each technology for each application is summarized in a single table.

MEASURES OF PERFORMANCE

The parameters selected for a performance comparison of the display technologies are summarized below. It is clear that the value of many performance parameters depend upon the particular conditions under which the technology has been applied. In order to make a fair comparison it is assumed that in all cases where such standardization is appropriate the application in mind is a 14 cm diagonal, direct-view display of 480 x 640 pixels. Since this specification essentially fixes the resolution it will not apply to the two parameters which measure resolution capability. This video application is fairly high up on the cost-complexity curve. By contrast, an alpha-numeric application would not offer as much challenge to an individual technology, and therefore would not highlight the performance comparisons as well. For less demanding applications there are a different set of trade-offs, and some of the data presented assuming the video application may not be appropriate.

Maximum Luminance

Luminance is defined as the emitted luminous intensity per unit area in candelas per square meter. The maximum luminance is the largest value of luminance expected from the technology when applied to the standard application defined above based upon what is known about the present state of the art within the technology. The definition applies only to active displays which emit their own light. The maximum luminance is important because it indicates how bright the display can be.

Maximum Reflectance Ratio

For passive displays the emitted luminous intensity is proportional to the incident luminous intensity. The ratio of the former to the latter is defined as the reflectance ratio. The maximum reflectance ratio is the largest value expected from the

technology when applied to the standard application defined above. It applies only to passive displays.

Contrast

Contrast is a controversial notion. We refer here to C_v , the ratio of the display foreground luminance less background, $L_f - L_b$, to the background luminance of the perceived display area, L_b .

$$C_v = \frac{L_f - L_b}{L_b}$$

The ambient lighting is specified at a level of 10^5 lux and the display is assumed to have 640 pixels per picture width. The tabulated value is the best expected, possibly with a contrast enhancing filter, for the technology under the specified conditions. It is important because of its influence on viewing performance. Passive displays may still require cockpit illumination due to veiling luminance. A passive display cannot be read without extra illumination when bright external light comes from in front of the aircraft even though it can be seen readily when bright external light comes from behind.

Efficiency

Efficiency is defined as the ratio of the luminous power output to the total electrical power input in units of lumens per watt. The total electrical power input includes the power dissipated in the drive electronics. High efficiency is desirable to limit heat dissipation.

Dimming Ratio

The dimming ratio is defined as the maximum luminance obtainable divided by the minimum luminance obtainable in a display device without extinguishing pixels. The definition is not applicable to a passive display. Dimming ratio is important in applications where the same device must be used in high ambient conditions such as sunlight as well as low ambient conditions such as during night operations.

Typical Resolution

Resolution is defined as the number of pixels per linear dimension. The adjective, typical, implies the maximum value that is associated with applications in each technology (the standard application described above does not apply to this parameter). The purpose of this performance measure is to indicate relative resolution capability as a function of technology.

Maximum Number of Pixels Per Picture Height

The purpose of this parameter is to indicate resolution capability in terms of picture height as opposed to linear dimension. In some technologies resolution is limited by

pixel size. In other technologies the limitation is on the maximum number of pixels. As above, the standard application does not apply and the purpose of the performance measure is to indicate relative resolution capability.

Gray Scales

The number of shades of light available in going from dark to bright measured by luminance gradations that differ by the square root of two. The number of gray scales is important because of its influence on visual perception and discrimination. For many applications of interest it is desirable to match the number of gray scales of the display to the number of quantization levels of the sensor.

Viewing Angle

The viewing angle is defined as the maximum angle in degrees at which the display can be viewed measured relative to the normal to the display face. For the LCD technology the maximum viewing angle can vary from 10 to 80 degrees depending upon how the technology is applied.

Current Color Capability

Current color capability refers to the ability of the technology to display simultaneously one, two or three primary colors, considering only present state-of-the-art and excluding future potential.

Storage Temperature Range

This is the temperature range over which the device can survive during storage. Three ranges are selected to correspond with typical military specifications.

Uncompensated Operating Temperature Range

This is the temperature range over which the device can carry out its desired function without degradation in performance.

Current System Cost (per pixel)

The purpose of this parameter is to indicate current relative cost of the individual technologies. Although cost is an extremely important parameter it is very difficult to specify quantitatively. Consequently, a relative scale is used for comparative purposes and is based on professional judgment.

Projected Cost (per pixel)

Because most of the display technologies are developing rapidly there is great potential for future reduction in the cost per pixel. This is indicated again by using a relative scale for comparative purposes and is based on professional judgment. The cost is for the system and includes the drive electronics.

Operating Life

Operating life is defined as the mean time to failure of operational displays measured in hours. It is specified in one of two ranges.

CAPABILITY OF TECHNOLOGY

A value for each measure of performance is tabulated in Table 1 for each display technology. The reader is cautioned that he must exercise care in the use of the table for a number of reasons. Firstly, in many cases there is a large uncertainty in the numerical values of the entry. Secondly, it is important to specify the conditions under which the numerical values apply. Many of these conditions have already been specified. However, not all of the conditions can be stated when trying to generalize over a technology that includes a large number of different individual devices. Thirdly, the technical area under consideration is growing rapidly and the information presented can become obsolete over a very short time interval. Finally, the data represent inputs from a number of qualified experts who exhibited strong differences of opinion on several crucial parameters. In some cases the data are based on an average or a majority vote which was reached only after heated debate. It is ironic that performance information which is the primary interest of the user is at the same time the most difficult information upon which to obtain a consensus from the experts. It must also be emphasized that the different characteristics specified in Table 1 are not necessarily obtainable simultaneously or in a single system. For example, a single CRT cannot obtain full color with the specified luminance and contrast all the same display.

While Table 1 is useful for a comparison of the technologies over a broad range, it certainly does not give the whole story. In an effort to round out the comparison a verbal summary of the advantages and disadvantages of each technology is included in Table 2

Several observations can be made following a study of Tables 1 and 2. The most obvious fact is that the mature CRT technology still dominates in almost all the performance measures with the notable exception of future projected cost per pixel. CRT is the only technology with full, current, color capability. The disadvantages of CRT are not extremely serious. LCD and EL have the potential for very low, future cost. However, cost is difficult to quantify and ultimate cost will depend heavily on applications in industries other than aerospace, particularly those associated with consumer products such as TV, watches, calculators and computers. When the other technologies are compared with CRT there is always at least one parameter where they perform poorly relative to the CRT. Those observations should be tempered by the fact that the performance comparison did use a standard application in which the CRT performs very well.

REQUIREMENTS FOR APPLICATIONS

The applications of electronic display technology to military aircraft are classified

Table 1 Performance Summary of Display Technologies

Note: Performance limits are not necessarily obtainable simultaneously or in a single display system.

Display Technology

Performance Parameter	CRT	VFD	LCD	PDP	LED	EL	ECD
Max. Luminance (Cd m^{-2}) (active display)	10^5	10^3	-	10^3	10^4	$5 \cdot 10^3$	-
Max. Reflectance Ratio (passive display)	-	-	.9	-	-	-	.8
Contrast $C_v = \frac{L_f - L_b}{L_b}$	10	<1	>10	1	1	3	>10
Efficiency (lumens per watt including drive electronics)	5	1	-	.1	.01	.2	-
Dimming Ratio (for active graphics display)	10^7	10^5	-	500	$>10^7$	$>10^7$	-
Typical Resolution (pixels per mm)	20	5	5	3	5	5	5
Max. no. of pixels per picture height	5000	500	1000	2000	500	1000	500
Gray Scales (over full ambient range in $\sqrt{2}$ steps)	10	1	4	4	6	8	4
Viewing Angle (maximum angle in degrees from normal)	80	70	10-80	80	60	80	80
Current Color Capability (M=mono; P=poly; F=full)	F	M	M	H	P	M	P
Storage Temperature Range (degrees C) Can meet:							
A) -55 to +125	A	A	B	A	A	A	A
Uncompensated Operating B) -25 to +80							
Temperature Range (deg. C) C) 0 to +50	A	A	C	A	B	B	B
Current System Cost (per pixel) H - High	L	L	M	H	H	L	L
M - Medium							
Projected Cost (per pixel) L - Low	L	L	VL	L	H	VL	L
VL - Very Low							
Operating Life (hours) A)10,000 hours; B) 5,000 hours	A	A	A	B	B	B	A

Table 2 Relative Advantages and Disadvantages

Technology	Advantages	Disadvantages
CRT	High resolution	High voltage
	Good addressability	Large depth
	High contrast	Limited life under high ambient light
	Flexibility	Corner edge focus circuitry
	Color capability	High maintenance cost
	Mature technology	Heavy
	High luminous efficiency	
VFD	Good reliability	Poor in high ambient light
	Mature technology	Limited ability for large matrix display
	Low production cost	Vibration sensitive
	Low voltage	Background glow (in some cases)
LCD	Passive display	Slow switching speed (in most cases)
	Low switching voltage	External illumination required
	Very high resolution possible	Temperature range
	No contrast loss in high ambient	Low yield
	Inherent memory possible	Addressing, multiplexing, viewing angle, and contrast can be problems
PDP	Inherent memory possible	Poor in high ambient
	High resolution	Generally orange
	No flicker for most	Limited dimming range
	High contrast ratio	Background glow (some cases)
	Rugged	
	Wide viewing angle for most	
	High MTBF	
	May be made transparent	
LED	Mature technology	
	Extremely fast	Short persistence
	High resolution	Poor luminous efficiency
	Rugged	Difficult to get uniform brightness
	Reliable	High peak currents
	Low voltage	No blue
		Expensive in large arrays
EL		Yield problem
	Rugged	Moderate luminous efficiency
	High contrast (black layer)	Moderate luminance
	Uniformity of brightness	
	Large size potential	
ECD	Potentially low cost	
	Passive display	External illumination required
	High contrast	Difficult to matrix address
	Inherent memory	Need more stable electrodes and electrolyte
		Slow switching speed

in the Cockpit Environment lecture. The ultimate goal is to make an assessment of the potential of each technology to satisfy the requirements of those specific applications. As an intermediate step it is desirable to identify the particular performance parameters which are important to each application. Of course, all the parameters can be important but some are more significant than others. At the outset maximum luminance was of such overriding importance that it was necessary to further break down the applications by specifying whether each would have to operate over the full range of ambient including direct sunlight or whether it would only have to operate over a restricted range of ambient such as that associated with a rear cockpit or internal cabin. In the latter case the requirement on maximum luminance is reduced. The head-up and helmet-mounted displays are always expected to meet the full range of ambient requirement unless restricted to night operations, where dimming ratio becomes of primary importance. The resolution parameters including gray scales are of major importance in the video and vector graphic applications. Efficiency is of major importance for helmet-mounted displays because of the undesirability of heat generation. In general, it is difficult to prove a requirement for color other than the motivation provided by the fact that pilots prefer color. Cost and long life are generally desirable features. High speed is desirable in video applications. Inherent memory is often desirable for the message and discrete applications.

TECHNOLOGY POTENTIAL

The major goal of this work has been to make an assessment of electronic display technology for military aircraft applications. To that end Table 3 has been prepared as a summary of the findings. While the kind of information contained therein is of major value to the users, it has not been easy to generate. The reason for the difficulty is that to be accurate it is necessary to predict the future. The numbers 1-5 were used to score the technology with the interpretation of each number as shown. Each member of the working group had the opportunity to prepare his own grade sheet at his leisure and with outside consultation. Then, in executive session, individual grades were combined to form a single set. There were considerable differences of opinion and the results represent a majority decision that was not always unanimous. While there was some individual bias, the group as a whole made every effort to be fair and consistent in their assessment. A study of Table 3 permits a number of observations to be made. The large number of ones associated with the CRT confirms the earlier observation that it is currently the dominant technology. The only applications where the CRT is not currently used are for the keyboard and alpha numeric classifications where the CRT is not expected to find use. Also as already observed, there are major differences in the technology potential depending upon whether the application requires operation over the full range of ambient. PDP, for example, as a mature technology is either qualified for, or in use in, almost all those applications except where a full range of ambient is specified. LCD does well in high ambient although extra illumination

Table 3 Application Assessment

Display Technologies	Applications																			
	Full range of ambient (front cockpit)												Restricted range of ambient (rear cockpit)							
	Video HUD	Vector-graphic HUD	Video HDD	Vector-graphic HDD	Video HMS	Vector-graphic HMS	Vector-graphic MMD	Message MMD	Message Keyboard	Discrete Keyboard	Message Alphanumeric	Discrete Alphanumeric	Video HDD	Vector-graphic HDD	Vector-graphic MMD	Message MMD	Message Keyboard	Discrete Keyboard	Message Alphanumeric	Discrete Alphanumeric
CRT	1	1	1	1	1	1	1	1	5	5	5	5	1	1	1	1	5	5	5	5
VFD	5	5	5	5	5	4	4	3	3	3	3	3	5	5	4	3	3	3	3	3
LCD	3	3	3	3	3	3	3	3	3	3	2	1	3	3	3	3	3	3	2	1
PDP	5	5	5	5	5	5	5	5	5	5	5	5	5	1	1	1	1	2	1	2
LED	5	5	5	4	5	3	3	3	3	3	2	1	5	2	2	2	2	2	1	1
EL	5	4	4	3	3	3	3	3	3	3	3	2	3	3	3	3	2	2	2	2
ECD	5	5	5	5	5	4	4	4	4	3	3	2	5	5	4	4	4	3	3	2

- 1 - Technology is now used in this application.
- 2 - Technology is qualified for this application.
- 3 - Technology could be qualified for this application in 5 years.
- 4 - Use of technology for this application is possible in longer time frame.
- 5 - Technology unlikely to find use here.

is required to take care of veiling luminance when bright external light comes from in front of the aircraft. Both LED and EL are more promising for the applications where they do not have to operate in high ambient. VFD is poor in high ambient light and, in general, is not yet promising for any of the applications. LCD as a passive display has the potential to qualify for all the applications. ECD which is also passive is generally not promising for the video applications primarily because of its slow switching speed and matrix addressing difficulties. The most promising of the new technologies are LCD, LED and EL. Comparing those three, LED appears to be the furthest developed at this point, but is not expected to find application at the video level. LCD has the edge in high ambient. Both LCD and EL hold promise for very low cost. It is difficult to pick an obvious winner among the three. Each technology has its own strong proponents based to some extent on how much they have invested in their technology choice.

SUMMARY

A comprehensive study of current modern display technology has been completed. An assessment of the potential of each technology to qualify for the applications of interest has been made. The CRT is and will remain for some time at the forefront of display technology for applications in military aircraft at the video end of the spectrum where operation is required over the full ambient range. The newer flat panel technologies will find their applications first at the message and discrete data end of the spectrum where the display needs to operate only over a restricted range of ambient light. PDP is the most mature of the new flat panel technologies and has already found application in military aircraft. It lacks potential for high ambient and video applications. It also has limited dimming range. LCD, LED, and EL are the more promising new contenders of the flat panel technology group, and it is difficult to pick a winner among the three. LED is the most developed. It is promising for its speed and resolution capability. It appears to be limited by poor luminous efficiency, its lack of blue color, and its higher cost in large arrays. LCD and EL show the greatest promise for very low cost. LCD has high resolution, however, an LCD video display is a long way from operational. Prospects for improvements are good through development of complex drive systems, special filters and temperature compensation. EL shows considerable promise but is expected to obtain only moderate luminance and luminous efficiency. VFD and ECD are expected to find only limited application in military aircraft. VFD appears attractive to the automobile market but is inadequate in high ambient. ECD is only in an advanced state of laboratory development. It is presently limited by slow switching speed and instability of electrodes and electrolytes. In summary, there are many continuing challenges to be met by modern display technology for applications in military aircraft, but the potential is very promising over the long run.

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